CHAPTER

3 Emissions Pricing to Stabilize Global Climate*

Valentina Bosetti
Fondazione Eni Enrico Mattei, Italy, and Centro Euro-Mediterraneo per i Cambiamenti Climatici

Carlo Carraro
University of Venice, Italy

Sergey Paltsev and John Reilly
Massachusetts Institute of Technology, United States

Key Messages for Policymakers

- Without significant emissions mitigation actions, projected "likely" global atmospheric temperature increases by the end of the century are approximately 2.5° C to 6.5° C above preindustrial levels.
- Although there is much uncertainty, a global carbon tax starting at roughly US$20 in 2020 and rising at 3 to 5 percent per year should be in line with stabilizing atmospheric greenhouse gas (GHG) concentrations at 650 parts per million (ppm) or keeping mean projected warming to about 3.6° C. A starting tax of roughly twice this level would be recommended if the goal is to keep atmospheric GHG concentrations to 550 ppm or mean projected warming below 3° C.
- However, keeping mean projected warming to 2° C (or stabilizing atmospheric GHG concentrations at current levels of about 450 ppm CO_2 equivalent), the goal identified in the Copenhagen Accord (COP 15) and reiterated in the Cancun Agreements (COP 16) is highly ambitious and may be infeasible. Achieving this

*This chapter is based on a policy note prepared for the IMF Workshop on Fiscal Policy and Climate Mitigation on September 16, 2011, in Washington, DC. We are grateful to Michael Keen, Ian Parry, and all the participants of the workshop for comments and suggestions. The usual disclaimer applies.

target would require the future development and wide-scale deployment of (still unproven) technologies that, on net, remove GHGs from the atmosphere. The Copenhagen pledges for 2020 still keep the 2° C target within reach—should these technologies be successfully developed—but highly aggressive actions would be needed immediately after that.

- Even the 550 ppm target would become technically out of reach if action by all countries is delayed beyond about 2030. And required near-term emissions prices (in developed economies) consistent with this target escalate rapidly with delayed action to control emissions in developing economies. Postponing mitigation actions, especially in emerging countries where large portions of energy capital are being installed for the first time, can be very costly. Extra costs associated with the delayed actions escalate rapidly with the stringency of the target, and some more stringent targets become infeasible if action is postponed.
- To reduce the cost while achieving an equitable sharing of them, decisions about where emissions reductions are taken and how they are paid for should be separated. Emission mitigation should take place where it is most efficient. Equity considerations can be addressed through agreed upon mechanisms that result in transfers from those better able to pay to those with less ability to bear these costs. Negotiating such a transfer scheme is likely one of the most difficult aspects of reaching an agreement.
- Innovation, both on energy efficiency and alternative energy sources, is needed. Carbon pricing (e.g., carbon taxes or a price established through a cap-and-trade system) would provide a signal to trigger both innovation and adoption of technologies needed for a low carbon economy.

In this chapter, we discuss projected greenhouse gas (GHG) emissions pricing paths that are potentially consistent with alternative targets for ultimately stabilizing the global climate system at the lowest economic cost and under alternative scenarios for country participation in pricing regimes. The pricing projections come from models that link simplified representations of the global climate system to models of the global economy, with varying degrees of detail on regional energy systems. There is considerable uncertainty surrounding future emissions prices, given that different models make very different assumptions about future emissions growth (in the absence of policy), the cost and availability of emissions-reducing technologies, and so on. Nonetheless, projections from the models still provide policymakers with some broad sense of the appropriate scale of (near-term and more distant) emissions prices that are consistent with alternative climate stabilization scenarios and how much these policies cost.

In the next section we discuss where we might be headed in the absence of mitigation policy, in terms of future GHG emissions trends, and what these imply for the growth of atmospheric GHG concentrations and, ultimately, for the amount of likely warming over this century. We also discuss the benefits of different stabilization targets for atmospheric GHG accumulations in terms of potentially avoiding warming. The chapter then addresses projected emissions pricing, as well as the costs of mitigation policies, to meet stabilization targets in the ideal (but unlikely) event of early and full global cooperation and with efficient pricing across all emissions sources and over time. This is followed by a discussion of the implications of delayed emissions reductions by all countries compared with just developing economies. We briefly evaluate recent emissions reduction pledges by country governments in light of the climate stabilization goals. The following section discusses the distributional burden of mitigation costs across countries and the potential complications for negotiation of long-term climate policy. In the final section, we offer some thoughts on pragmatic policy steps in the near term.

Emissions and Warming Trends

Emissions

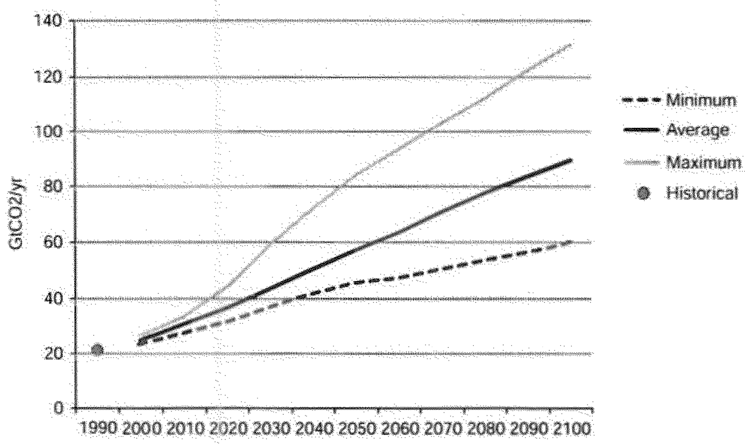
There have been many efforts to project future emissions trends, and the range of projections over the twenty-first century has been wide. GDP and population expansion are major drivers of future emissions growth, although the role of the latter will gradually fade with the projected stabilization of the world population in the second half of the century. Some factors tend to dampen future emissions growth, such as potentially rising fossil fuel prices and improvements in energy efficiency (e.g., cars that can be driven longer distances per unit of fuel or buildings that require less energy to heat them). What differs most across forecasting models—and causes the uncertainty affecting emissions projections—are assumptions concerning future GDP growth; the availability of fossil resources; the pace and direction of technical change, in turn affecting the cost of low-carbon technologies and the energy intensity of the economy; and flexibility of fuel and technology substitution within the energy-economic system. Whether and when governments of high-emitting countries undertake meaningful GHG mitigation measures is an additional uncertainty on top of the various economic forces.

In the absence of (significant) mitigation action, energy-related carbon dioxide emissions (the primary GHG) are projected to increase substantially during the twenty-first century. Figure 3.1 shows the range of projections in a recent model comparison exercise organized by Stanford University's Energy Modeling Forum (EMF-22), which engaged 10 of the world's leading integrated assessment models.[1] On average, fossil fuel CO_2 emissions will grow from about 30 Gt CO_2 in 2000 to almost 100 Gt CO_2 by 2100.

[1] See Clarke and others (2009); four of the integrated assessment models participated with two alternative versions for a total of 14 models.

ED_442-001040137

Figure 3.1. Energy-Related CO_2 Emissions Projections over the Twenty-First Century



Source: Authors' calculations drawing from the EMF-22 dataset.

Note: The figure indicates a range of the median projections from each model used in the EMF-22 study.

The contribution of different regions to global CO_2 emissions is more stable across models. The Organization for Economic Cooperation and Development (OECD) countries will contribute 15 to 25 percent to total emissions in 2100 (compared with just under half of global emissions at present). Although the United States continues as one of the main emitters, its projected global emissions share will decrease from 25 percent to 10 percent over the century. Brazil, Russia, India, and China (BRIC) will contribute about 45 to 50 percent of total fossil CO_2 emissions by 2050, with at least 25 percent of the total emissions attributed to China alone from 2020 onwards. India accounts for a further 15 percent of global emissions by the mid-century. The rest of the developing world is projected to have an increasing role, moving from 17 to 25 percent of total emissions at present to 25 to 40 percent by 2100.

Anthropogenic CO_2 emissions are mostly energy related, with a (small) contribution from industrial processes (mostly cement production) and a (more substantial) contribution from land-use change, although energy-related emissions are projected to grow faster than these other sources of CO_2. Destruction of tropical forests and peat lands contributed 25 percent of global CO_2 emissions in 2000, mostly from a subset of tropical countries including Brazil, Indonesia, and some countries in central and western Africa.

While CO_2 is the major contributor to global warming, other GHGs also play a significant role. In particular, these include five other gases covered by the Kyoto Protocol: methane (CH_4), nitrous oxide (N_2O), and a group of so-called F-gases (HFCs, PFCs, and SF_6).[2] Currently, these non-CO_2 gases contribute about 25 percent of total annual GHG emissions in CO_2-e (i.e., CO_2 warming equivalents over their atmospheric life span), although again, these emissions are projected to grow slower than CO_2 emissions over the twenty-first century (IPCC, 2007).[3]

Implications for Future Atmospheric Concentrations and Temperatures

Once absorbed by the atmosphere, some GHGs are largely irreversible—CO_2 emissions, for example, reside in the atmosphere for about 100 years.[4] Without a significant emissions control policy, atmospheric GHG concentrations are projected to grow rapidly. The EMF-22 scenarios project atmospheric concentrations of 800 to 1,500 parts per million (ppm) CO_2-e by 2100 (counting concentrations of the gases identified for control in the Kyoto Protocol). For comparison, concentrations in 2010 were about 440 ppm.[5]

To date, temperatures are estimated to have risen by approximately 0.75° C relative to preindustrial levels, with most of the warming attributed to atmospheric GHG accumulations as opposed to other factors like urban heat absorption, volcanic activity, and changes in solar radiation (IPCC, 2007). However, the full impact of historical concentrations has yet to be felt due to inertia in the climate system (gradual heat diffusion processes in the oceans slow the adjustment of temperatures to higher GHG concentrations).

According to IPCC (2007), in the absence of a GHG mitigation policy, projected "likely" temperature increases by the end of the century are in the range of 2.4° C to 6.4° C above preindustrial levels ("likely" refers to a 66 percent chance or greater). A recent study at the Massachusetts Institute

[2] The major sources of F-gases are air conditioning, semiconductor production, electrical switchgear, and the production of aluminum and magnesium.
[3] Other substances will also affect future climate. These include chlorofluorocarbons (CFCs), whose emissions were largely phased out under provisions of the 1987 Montreal Protocol, but remain in the atmosphere as a powerful contribution to warming, and other short-lived warming substances like ozone and particulates. These substances add about another 30 ppm to atmospheric CO_2-e. On the other hand, some substances, particularly sulfates, have a cooling effect through deflecting incoming sunlight.
[4] Methane lifetime is about 12 years, nitrous oxide about 115 years, while F-gases lifetimes are thousands of years.
[5] It is important to distinguish between the concentrations of all GHGs and a subset of the Kyoto gases. In 2010, the CO_2 concentration was about 385 ppm and the Kyoto gases concentration was about 440 ppm CO_2-e, while for all GHGs, concentration was about 465 ppm CO_2-e. For more discussion on this issue, see Huang and others (2009).

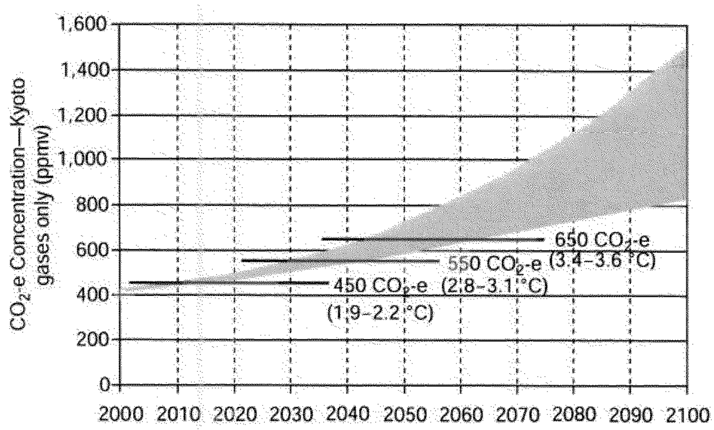
of Technology (MIT) with updated climate and socioeconomic parameters projected even more warming—a 90 percent chance that temperatures will rise by 3.8° C to 7.0° C by 2100 with a mean projection of 5.2° C (Sokolov and others, 2009).

Yet another recent and especially comprehensive study by Prinn and others (2011) put together findings from intergovernmental panels (represented by the IPCC); national governments (including selected scenarios from the U.S. government Climate Change Science Program [US CCSP]); and industry (represented by Royal Dutch Shell). Prinn and others (2011) estimate global temperature increases of 4.5° C to 7.0° C from current levels by 2100 in the absence of climate policy. There are many risks associated with higher levels of temperature increase, some of which (particularly the risk of abrupt climate change) are poorly understood (see Chapter 4 and IPCC, 2007).

Avoiding Warming under Different Climate Stabilization Targets

Stabilization of GHG concentrations at levels often discussed in international negotiations would require very substantial emissions cuts. As indicated in Figure 3.2, some of the more stringent targets are already exceeded or will be exceeded in the not-so-distant future. In particular, the 450 CO_2-e target for

Figure 3.2. Relationship between Different CO_2-e Concentration Targets and Projected Concentrations in the Absence of Mitigation



Source: EMF-22 (Clarke and others, 2009).

Note: Figures in parentheses indicate mean projected warming (above preindustrial levels) if concentrations are stabilized at particular levels assuming a value of climate sensitivity equal to three.

the Kyoto Protocol gases (consistent with keeping mean projected warming above preindustrial levels to approximately 2° C) is about to be passed.

Although the most stringent concentration targets might be beyond reach, even limited actions to reduce GHGs will appreciably reduce the probability of more extreme temperature increases. For example, according to results reported in Table 3.1, stabilizing GHG concentrations at 660 ppm rather than 790 ppm reduces the risk that warming in 2100 will exceed 4.75° C, going from 25 percent to less than 1 percent.[6]

But what scale of (near-term and more distant) emissions prices are needed to meet alternative stabilization targets and how much might these pricing policies cost? The answers depend, among other factors, on which countries participate in pricing regimes and the efficiency of the policies used to achieve emissions reductions. We turn to these issues in the next two sections, beginning first with the ideal global policy response with early and full participation in pricing regimes and then with more realistic scenarios with delayed action among all or a subset of countries.

Climate Stabilization with Global Participation of Countries

Here we consider a policy scenario with efficient (i.e., cost-minimizing) pricing of emissions across regions, different gases, and time, and full credibility of

Table 3.1. Cumulative Probability of Global Average Surface Warming from Preindustrial Levels to 2100

	$\Delta T > 2°C$	$\Delta T > 2.75°C$	$\Delta T > 4.75°C$	$\Delta T > 6.75°C$
No Policy at 1400	100%	100%	85%	25%
Stabilize at 900	100%	100%	25%	0.25%
Stabilize at 790	100%	97%	7%	<0.25%
Stabilize at 660	97%	80%	0.25%	<0.25%
Stabilize at 550	80%	25%	<0.25%	<0.25%

Source: Adapted from Webster and others (2009).
Note: Results are based on 400 simulations of the MIT's Integrated Global System Model under different assumptions about future emissions growth and parameters in the model. As the increase in global temperature from preindustrial levels to 2000 was about 0.75° C, probabilities for temperature increases relative to 2000 can be obtained by subtracting 0.75° C from the targets in the top row.

[6] The estimates in Table 3.1 should not be taken too literally, as they depend on assumptions about the probability distribution for warming at different long-term concentration levels, which are uncertain. The point is just that the risk of more extreme warming outcomes can be diminished sharply by stabilizing at lower GHG concentration levels.

future policies in triggering long-term investments. The ideal case is useful to understand the basic dynamics of the system and to have a benchmark for evaluating how far more realistic policy scenarios diverge from the ideal policy.

Achieving global economic efficiency (i.e., reaching a climate stabilization target at the lowest global economic cost) involves pricing emissions at the same rate across different countries. This can be achieved by imposing the same GHG price across the countries through a system of carbon taxes or by allowing a full trade in emissions permits among all countries and all sectors of the economy.

One caveat is that the focus here is on the total global costs of policies and not the cost that might be borne by individual countries. As discussed further below, there are numerous possibilities for sharing the burden of mitigation costs across different countries. Another caveat is that possibilities for reduced deforestation in tropical countries and reforestation of temperate regions are not captured in the model results discussed below, even though they could contribute significantly to mitigation efforts.[7]

Emissions Prices and Emissions Reductions

Projected emissions prices (in CO_2-e for all GHGs and in 2005 U.S. dollars) and CO_2 reductions for different concentration targets in the EMF-22 exercise are summarized in Table 3.2, where the ranges include cases that do and do not permit transitory overshooting of the long-term stabilization target.

The global emissions price in 2020 that would be in line with a 650-ppm CO_2-e target ranges between \$3 and \$20 per metric tonne of CO_2-e across the different models. Emissions prices in 2020 are \$4 to \$52 per tonne under the 550 ppm CO_2-e target (or \$10 to \$52 per tonne if overshooting is not permitted). For the 450 ppm CO_2-e target, only two models find a solution when no overshooting is allowed: with overshooting, half of the models are able to find a solution, although the 2020 emissions price is generally quite high at \$15 to \$263 per tonne.

The reason models are less capable of finding a feasible set of actions for more stringent targets is that concentrations are already very close to 450 ppm

[7] There may be significant and relatively low cost opportunities for reducing emissions through protecting and enhancing global forest carbon stocks. Reducing emissions from deforestation and forest degradation (REDD) could lower the total costs of climate stabilization policies by around 10 to 25 percent or, alternatively, enable additional reductions of about 20 ppm CO_2-e with no added costs compared to an energy sector–only policy (see Chapter 5 and Bosetti and others, 2011). However, implementation issues would need to be overcome (see Chapter 5): most of the rainforest countries have not yet developed the implementation capacity for monitoring and enforcing country-level projects, which might diminish the role of REDD in the next decade.

Table 3.2. Emissions Prices and Reductions under Climate Stabilization Scenarios: Full Global Participation

Atmospheric stabilization target, ppm CO_2-e	Emissions price in 2020 (2005 US$ per tonne of CO_2-e)[a]	Percent change in global CO_2 emissions in 2020 relative to 2000	Percent change in global CO_2 emissions in 2050 relative to 2000
450[a, b]	15-263	–67 to 31	–13 to –92
550[b]	4-52	–4 to 50	–67 to 52
650	3-20	30 to 57	–16 to 108

Source: Authors' elaboration of the EMF-22 dataset.
[a]Only a limited number of the models are able to solve for this case (even with overshooting) as it requires the development and wide-scale deployment of negative emission technologies.
[b]Includes cases both with and without transitory overshooting of the long-term stabilization target. In the 650-ppm case, there is no overshooting.

CO_2-e (Figure 3.2). Stabilizing at 450 ppm CO_2-e would require an immediate and almost complete decarbonization of the entire global economy, which is most likely technically infeasible.[8] Similarly, going back to the target after overshooting implies deployment on a massive scale of "negative emissions technologies" to remove CO_2 from the atmosphere, particularly biomass power generation coupled with carbon capture and storage (BECS). Not all models envision the future deployment of such technologies, which are highly speculative at present.[9]

For cost-effectiveness over time, the emissions price should rise at (approximately) the discount rate (or rate of interest) to equate the (present value) of incremental abatement costs at different points in time (in emissions trading systems the allowance price would increase over time at this rate if there is perfect substitutability of trading in emissions permits and other financial instruments). Different modeling groups assume different (real) discount rates, usually in the range of 3 to 5 percent, so the carbon price would also increase over time at this rate.

Looking at emission reductions (expressed as percentage changes with respect to 2000 emissions), which need to be in line with the different targets (see the second and third column in Table 3.2) for the near- and medium-term, there is not much difference in appropriate emission reductions for 550 and 650 ppm—but very large emission reductions are required, even in the short term, for the 450 ppm CO_2-e scenario.

[8] A small amount of GHGs can be emitted to offset the annual decay of GHGs in the atmosphere.
[9] Another negative emissions possibility is filters for direct removal of CO_2 out of the atmosphere, but these technologies (which are extremely costly and energy intensive at present) were not incorporated in the EMF-22 models.

Policy Costs

Ideally, mitigation costs would be measured by economic welfare losses (see Chapter 1 and Paltsev and others, 2009), although GDP losses are more commonly reported in climate policy models.

EMF-22 reports the net present value of GDP costs (discounted at 5 percent) in the range of $0 to $24 trillion (in 2005 U.S. dollars) for 650 ppm CO_2-e stabilization, in the range of $4 to $65 trillion (in 2005 U.S. dollars) for 550 ppm CO_2-e stabilization, and $12 to $125 trillion for 450 ppm CO_2-e stabilization, considering the full range of scenarios.

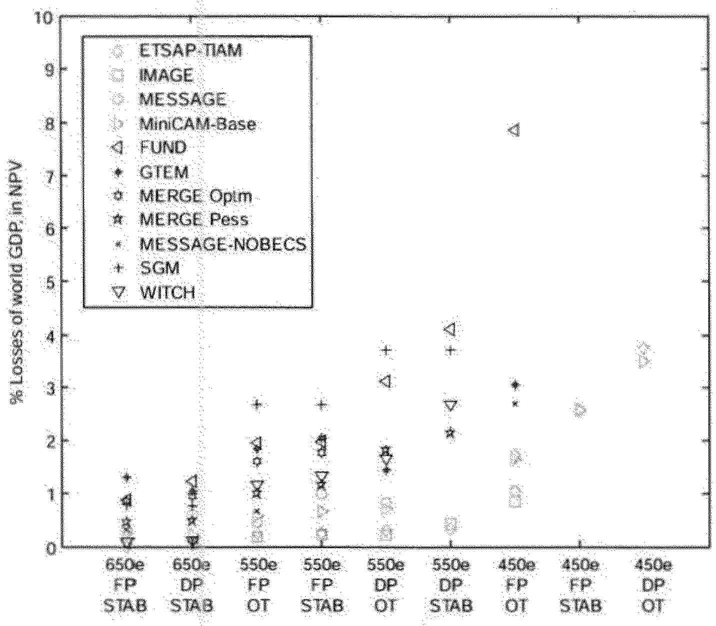
Figure 3.3 reports costs for each participating model for the three different stabilization levels and considering different levels of participation (full participation and delayed participation) and paths with and without overshooting of the target. Concentrating here on the full participation cases, costs, expressed as a percent of the present value of world GDP, are approximately 0.1 to 1.5 percent, 0.3 to 2.8 percent, and 2.7 percent for the three concentration targets, respectively.

US CCSP (Clarke and others, 2007) also reported the cost of climate policy as a percentage reduction in the global GDP, but rather than net present values, they reported the loss in different periods of time. The most stringent stabilization level in this study is roughly equal to 550 ppm CO_2-e (450 ppm when only CO_2 contributions are considered). The loss of the world GDP in comparison to a scenario with no climate policy is in the range of 1 to 4 percent in 2040 and 1 to 16 percent in 2100.

Emissions pricing will induce emissions reductions in the sectors where these reductions are cheapest. Models have different views about the timing of emissions reduction, but most of the projections agree that the power generation sector will be the first area where less-carbon-emitting (e.g., natural gas) or almost-zero-carbon-emitting technologies (e.g., nuclear, hydro, renewables) are introduced because of various economic substitutes that already exist in this sector.[10] Less-emitting technologies in transportation (e.g., gasoline/electric hybrid vehicles, more fuel-efficient conventional vehicles) and energy-saving technologies in buildings and industry are also promising, but they currently look more expensive. Substantial reductions in GHG emissions in agriculture and cement production are also costly, but to achieve climate stabilization, emissions from all sectors of the economy need to be reduced drastically.

[10] Jacoby, O'Sullivan, and Paltsev (2012) provide an assessment of the role of natural gas in a potential U.S. climate policy considering recent shale gas development.

Figure 3.3. Policy Costs for the EMF-22 Dataset by Model Run



Source: Tavoni and Tol (2010).

Note: Green colors indicate models with biomass generation coupled with carbon capture and storage (BECS) and blue models without BECS. FP = full, immediate participation of developing economies, DP = delayed participation of developing economies, STAB = target not to exceed, and OS = target can be overshot.

For more stringent climate stabilization targets, these reductions obviously need to begin in the near future. Deferring the bulk of mitigation action to later periods can make sense if we are optimistic about the availability, cost, and speed of deployment of low-emission technologies. A further degree of freedom is represented by negative emissions technologies. However, relying on a technological future that might not evolve as expected comes at a risk of missing the target completely.

Delayed Action and Incomplete Participation

Here we discuss how delaying mitigation action and incomplete participation among countries in pricing agreements affects the feasibility of climate stabilization targets and the emissions prices and costs associated with those targets.

For a given stabilization target, delayed global action implies that once global GHG emissions have peaked, they must then be reduced at an even faster rate, which could require an abrupt and very costly replacement of capital. In fact, if the world continues according to business as usual until 2030, according to most models, stabilization at 550 ppm CO_2-e will no longer be possible (at least leaving aside highly optimistic scenarios for the development and deployment of negative emission technologies). This target might still be feasible if ambitious mitigation policies at the global scale are postponed until 2020, but this delay could substantially scale up global mitigation cost.

Rather than complete global inaction, more likely we will face asymmetry of actions across regions of the world. Significant mitigation actions are planned to take place in some developed economies within the next decade (e.g., the EU has pledged, by 2020, to reduce GHGs by 20 percent below 1990 levels). However, it is unlikely that emerging economies will make substantial emissions reductions in the coming decade.

Even asymmetric participation may rule out some of the more stringent targets, while scaling-up the global costs of those stabilization scenarios that remain feasible. Inaction in developing economies clashes with the fact that the bulk of emissions in the next decades will be coming from non-OECD countries.

If CO_2 emissions are not regulated in some major emitting countries, several inefficiencies arise. At a given point in time, low-cost mitigation opportunities in countries without a mitigation policy will go unexploited, while other countries must bear a greater burden of mitigation costs. A dynamic inefficiency also arises, as unregulated countries are those where most new investments will take place. Investing instead in fossil technologies, fast-growing countries may lock in these long-lived technologies (e.g., a new coal plant may be in use for 50 years), and later conversion to low-carbon technologies becomes more costly, or simply impossible, if early scrapping is deemed unfeasible. Finally, nonparticipating countries might react to lower fossil fuel prices (arising from decreased fuel demand in participating countries) and increase their emissions, thus partially offsetting the environmental benefit of early movers, though studies suggest this carbon leakage effect is not too large.[11] One solution, frequently discussed by economists, is the use of incentive systems (as for example an evolution of the Clean Development Mechanism) to induce reductions in developing economies while limiting leakage (e.g., Bosetti and Frankel, 2009).

[11] Most studies report carbon leakage from the Kyoto Protocol targets being in the range of 5 to 15 percent. See IPCC (2007), section 11.7.2.1 at: http://www.ipcc.ch/publications_and_data/ar4/wg3/en/ch11s11-7-2-1.html.

Figure 3.3 again reports results from EMF-22, which looked extensively into climate agreements with incomplete country participation. We now concentrate on the delayed participation cases for each stabilization level.

A key result is that even in the limited number of models that suggest that the 450 ppm CO_2-e stabilization scenario is feasible with early and full global cooperation over emissions mitigation (i.e., models with BECS technologies), the target becomes infeasible if only the OECD immediately undertakes mitigation action while BRICs and the rest of the world remain on their business-as-usual path until 2030 and 2050, respectively.

When participation of developing economies is delayed, half of the models cannot find a feasible set of investment actions that allow attaining the 550 ppm CO_2-e scenario. Still, with overshooting, the CO_2 emissions price faced by OECD countries in 2020 increases, on average, by a factor of three. On the other hand, delayed participation by developing economies does not make much difference to costs in the 650 CO_2-e stabilization scenario. In this case, there is much greater scope for additional mitigation by all countries in the second half of the century to offset the foregone reductions early in developing economies, while still keeping within the concentration target.

A further point from Figure 3.3 is the wide range of disagreement across models, depending on assumptions about flexibility of substitution across technologies and, once more, on the assumptions concerning the availability of BECS (green versus blue markers in Figure 3.3 distinguish models with and without BECS technologies).

The set of technologies that will be available and the speed at which they will be deployed can crucially affect not only the costs of any climate policy, but also the time we can wait while still staying on track with a climate stabilization target. The stricter the climate objective or the later the mitigation effort starts, the greater the need to develop technologies (such as BECS and CCS) that have potential implications that we have not yet fully understood. This obviously requires a careful and realistic estimation of the costs and potentials of these technologies, the research, development, and demonstration requirements to make them available with a reasonable level of certainty, and the potential barriers and possible adverse side effects (e.g., CO_2 leakage from storage sites) that might be linked to their deployment on a large scale.

How do projections we have discussed so far compare with the current state of climate negotiations? At the 2011 climate change meetings in Durban, South Africa (COP-17), for the first time, it was formally agreed that developing economies should be part of any future international emissions control regime (which is a step forward), although any control regime will not come into force before 2020 at the earliest. Prior to the meeting in Durban, countries agreed on submitting their emissions reduction "pledges" during the 2009 COP-15 in Copenhagen, Denmark, and the 2010 COP 16 in Cancun, Mexico, where most developed economies submitted their emissions reductions targets relative to emissions in 1990, 2000, or 2005.[12] Brazil, Indonesia, Mexico, the Republic of Korea, and South Africa proposed reductions relative to their business-as-usual emissions,[13] and China and India submitted carbon intensity reduction targets (i.e., CO_2 emissions per unit of GDP). Some of the pledges have conditions attached, such as the provision of finance and technology or ambitious actions from other countries, while some pledges were provided as ranges. This leads to some flexibility in their implementation and a range of potential outcomes.

Therefore, implications of these pledges for 2020 global emissions will depend on what pledges are implemented and what rules will be applied. Many scientific groups have estimated global emissions in 2020 based on the Copenhagen Accord pledges. The 2010 Emission Gap Report (UNEP, 2010) collected these estimates and showed that emissions in 2020 could be as low as 49 Gt CO_2-e (a range of 47 to 51 GtCO_2-e) when countries implement their conditional pledges in their more stringent form, or as high as 53 GtCO_2-e (a range of 52 to 57 GtCO_2-e) if pledges are implemented in their more lenient form.

Emission pathways consistent with a "likely" chance of meeting the 2° C limit generally peak before 2020, have emission levels in 2020 around 44 GtCO_2-e (a range of 39 to 44 GtCO_2-e), have extremely steep emission reductions afterward, and/or reach negative emissions in the longer term. Hence, the ranges implied by Copenhagen pledges do not necessarily rule out the 2° C target, as the two ranges are not severely distant from one another. However, as previously discussed, the larger the overshoot will be, the faster the decarbonization in the second half of the century will be needed, with all the implications that we have discussed in this chapter.

Who Bears the Costs of Abatement?

Distinguishing between who incurs mitigation costs and who actually implements mitigation activities is important. For example, mitigation might

[12] Typical targets for developed regions like Canada, the European Union, Japan, and the United States are in the range of 20 percent GHG reduction relative to 2000 levels.

[13] Targets expressed with respect to baseline emissions are particularly tricky as they can be interpreted in very different ways depending on the baseline projection adopted.

happen in developing economies but be financed by developed economies through an emissions offset program. Internationally allocating a given amount (typically determined by the stabilization target) of allowable emissions affects costs and who pays. This distributional issue would be extremely relevant both in the case of taxes and in that of permits. A number of possibilities for distributing the shares of emissions reduction among participating countries have been analyzed. Reductions might be based on equal percent reduction, GDP per capita, population, emissions intensity, historical responsibility, or many other alternative ways. As any of the schemes benefits (or imposes the cost on) countries unevenly in different aspects of socioeconomic indicators, there is no unique formula that would satisfy all participating countries.

There are two interacting equity concerns that would have to be dealt with in seeking the global emissions goal. First, incentives and compensation for developing economy participation will be required consistent with the principle of common but differentiated responsibilities. Second, since mitigation costs and compensation payments by developed economies will be substantial, they also will need to find an acceptable burden-sharing arrangement among themselves. Simple emissions reduction rules are incapable of dealing with the highly varying circumstances of different countries.

Successful climate negotiations will need to be grounded in a full understanding of the substantial amounts at stake. For example, for a 50 percent global GHG reduction by 2050 relative to 2000 (with full global participation in emissions pricing), Jacoby and others (2009) estimated that if developing economies (including China and India) are fully compensated for the costs of mitigation in the period up to 2050, then the average cost to developed economies is about 2 percent of the GDP in 2020 (relative to reference level), rising to 10 percent in 2050.[14] The implied financial transfers are huge—over US$400 billion per year in 2020 and rising to about US$3 trillion in 2050—with the United States' share amounting to US$200 billion in 2020 and over a trillion dollars in 2050.

It is surely extreme to assume that developing economies will demand complete compensation. Also, the amount of compensation is smaller if it only covers direct mitigation costs and not other losses, as might come through terms-of-trade effects.[15] Nonetheless, international financial transfers under more aggressive climate stabilization targets would remain of

[14] The required carbon prices in this exercise are rising from about US$75/$tCO_2$ in 2020 to about US$400/$tCO_2$ in 2050.

[15] In this case, the annual financial transfers to developing economies are lower by US$77 billion in 2020 and by US$108 billion in 2050 (Jacoby and others, 2009).

unprecedented scale and seem highly unrealistic (at least in the near term), given large budget deficits at present.[16] This further underscores the huge challenges to reaching a global agreement on rapid climate stabilization, challenges that only grow over time, when developing economies are expecting substantial compensation.

Yet another problem is that, besides being substantial, mitigation costs can also vary widely across countries. For example, mitigation costs are higher in energy-exporting countries, while energy importers have some terms-of-trade gains due to lower fossil fuel prices that allow them to reduce the cost of participating in emissions control regimes. Mitigation costs will also be greater in countries more dependent on carbon-intensive fuels and that employ inefficient mitigation instruments. Potential climate change damages also vary widely across countries but in a very different way. All these distributional impacts need careful study, as they complicate negotiation of long-term climate stabilization policy.

Conclusion

Advocates of rapid climate stabilization might be dismayed by some of the harsh technical, economic, and practical realities discussed in this chapter. Keeping mean projected warming above preindustrial levels to 2.0° C or stabilizing atmospheric GHGs at 450 ppm (about the current level) would require rapid widespread international adoption of emissions control policies and the development, and global deployment, of negative emission technologies later in the century to reverse atmospheric accumulations after a period of overshooting the long-term concentration target. Even the 550 ppm target (mean projected warming of 2.9° C) is extremely challenging, not least because required emissions prices escalate rapidly with further significant delay in controlling global GHGs, and the annual transfers to provide some compensation for developing economies are large and contentious to design. On the other hand, near-term emissions prices that are consistent with the 650 ppm target are more moderate, and delayed action on emissions reductions is less serious for this case, although obviously this target entails greater risks of dangerous warming.

The huge uncertainties—surrounding both the extent of climate change associated with a given atmospheric concentration target and our ability to develop technologies that would enable a rapid stabilization of the climate if the earth warms up rapidly—point to the importance of putting a policy architecture in place in the near term and delaying decisions about how

[16] Even one of the Copenhagen Accord goals of raising US$100 billion per year by 2020 for climate finance from "a wide variety of sources" seems extremely challenging at this point (see Chapter 7).

rapidly emissions should be scaled back in the distant future until some of the uncertainties have been resolved. Aiming for a CO_2 price somewhere in the ballpark of US$20 per tonne for 2020 applied across major emitting (developed and developing) countries seems reasonable and is roughly consistent with emissions prices suggested by the benefit-cost approach discussed in Chapter 4. Compensation issues for developing economies should also be more manageable at this level of pricing.

References and Suggested Readings

For details on the EMF-22 modeling exercise, see the following:

Clarke, L., J. Edmonds, V. Krey, R. Richels, S. Rose, and M. Tavoni, 2009, "International Climate Policy Architectures: Overview of the EMF 22 International Scenarios," *Energy Economics,* Vol. 31 (Supplement 2), pp. S64–S81.

For an overview of future emissions reduction pledges by different countries, see the following:

www.unep.org/climatepledges.org.

For a discussion concerning the potential role of bio-energy and carbon capture and storage (CCS) technologies on the costs of stringent policy, see the following:

Tavoni, M., and R. S. J. Tol, 2010, "Counting Only the Hits? The Risk of Underestimating the Costs of Stringent Climate Policy," *Climatic Change*, Vol. 100, pp. 769–778.

For a discussion about potential technological and economic obstacles for air capture technologies, see the following:

Ranjan, M., 2010, "Feasibility of Air Capture" (master's thesis; Cambridge, Massachusetts: Engineering Systems Division, Massachusetts Institute of Technology), available at http://sequestration.mit.edu/pdf/ManyaRanjan_Thesis_June2010.pdf.

Other publications:

Babiker, M., J. Reilly, and L. Viguier, 2004, "Is International Emissions Trading Always Beneficial?" *Energy Journal*, Vol. 25, No. 2, pp. 33–56.

Bosetti, V., and J. Frankel, 2009, "Global Climate Policy Architecture and Political Feasibility: Specific Formulas and Emission Targets to Attain 460 ppm CO_2 Concentrations," NBER Working Paper No. 15516, (Cambridge, Massachusetts: National Bureau of Economic Research).

Bosetti, V., R. Lubowski, A. Golub, and A. Markandya, 2011, "Linking Reduced Deforestation and a Global Carbon Market: Implications for Clean Energy Technology and Policy Flexibility," *Environment and Development Economics*, Vol. 16, No. 4, pp. 479–505.

Clarke, L., J. Edmonds, H. Jacoby, H. Pitcher, J. Reilly, and R. Richels, 2007, "Scenarios of the Greenhouse Gas Emission and Atmospheric Concentrations," Subreport 2.1A of Synthesis and Assessment Product 2.1 by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research (Washington: Department of Energy, Office of Biological and Environmental Research).

Edenhofer, O., C. Carraro, J. C. Hourcade, K. Neuhoff, G. Luderer, C. Flachsland, M. Jakob, A. Popp, J. Steckel, J. Strohschein, N. Bauer, S. Brunner, M. Leimbach, H. Lotze-Campen, V. Bossetti, E. de Cian, M. Tavoni, O. Sassi, H. Waisman, R. Crassous-Doerfler, S. Monjon, S. Dröge, H. van Essen, P. del Río, and A. Türk, 2009, "RECIPE—The Economics of Decarbonization," synthesis report. Available at: www.pik-potsdam.de/recipe.

Huang, J., R. Wang, R. Prinn, and D. Cunnold, D., 2009, "A Semi-Empirical Representation of the Temporal Variation of Total Greenhouse Gas Levels Expressed as Equivalent Levels of Carbon Dioxide," Report 174 (Cambridge, Massachusetts: Massachusetts Institute of Technology, Joint Program on the Science and Policy of Global Change), available at http://globalchange.mit.edu/pubs/abstract.php?publication_id=1975.

IPCC, 2007, *Climate Change 2007: Mitigation of Climate Change.* Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, 2007. (New York: Cambridge University Press).

Jacoby, H., M. Babiker, S. Paltsev, and J. Reilly, 2009, "Sharing the Burden of GHG Reductions," in *Post-Kyoto International Climate Policy: Summary for Policymakers*, ed. by J. Aldy and R. Stavins (Cambridge, UK: Cambridge University Press), pp. 753–785.

Jacoby, H., F. O'Sullivan, and S. Paltsev, 2012, "The Influence of Shale Gas on U.S. Energy and Environmental Policy," *Economics of Energy and Environmental Policy*, Vol. 1, No. 1, pp. 37–51.

Morris, J., J. Reilly, and S. Paltsev, 2010, "Combining a Renewable Portfolio Standard with a Cap-and-Trade Policy: A General Equilibrium Analysis," Report 187 (Cambridge, Massachusetts: Massachusetts Institute of Technology, Joint Program on the Science and Policy of Global Change), available at: http://globalchange.mit.edu/pubs/abstract.php?publication_id=2069.

Paltsev, S., J. Reilly, H. Jacoby, and K. Tay, 2007, "How (and Why) Do Climate Policy Costs Differ Among Countries?" in *Human-Induced Climate Change: An Interdisciplinary Assessment*, ed. by M. Schlesinger, Haroon S. Kheshgi, Joel Smith, Francisco C. de la Chesnaye, John M. Reilly, Tom Wilson, and Charles Kolstad (Cambridge, UK: Cambridge University Press), pp. 282–293.

Paltsev, S., J. Reilly, H. Jacoby, and J. Morris, 2009, "The Cost of Climate Policy in the United States," Report 173 (Cambridge, Massachusetts: Massachusetts Institute of Technology, Joint Program on the Science and Policy of Global Change), available at http://globalchange.mit.edu/pubs/abstract.php?publication_id=1965.

Prinn R., S. Paltsev, A. Sokolov, M. Sarofim, J. Reilly, and H. Jacoby, 2011, "Scenarios with MIT Integrated Global System Model: Significant Global Warming Regardless of Different Approaches," *Climatic Change*, Vol. 104, No. 3-4, pp. 515–537.

Sokolov, A., P. Stone, C. Forest, R. Prinn, M. Sarofim, M. Webster, S. Paltsev, A. Schlosser, D. Kicklighter, S. Dutkiewicz, J. Reilly, C. Wang, B. Felzer, J. Melillo, and H. Jacoby, 2009, "Probabilistic Forecast for 21st Century Climate Based on Uncertainties in Emissions (Without Policy) and Climate Parameters," *Journal of Climate*, Vol. 22, No. 19, pp. 5175–5204.

United Nations Environment Programme, 2010, "The Emissions Gap Report: Are the Copenhagen Accord Pledges Sufficient to Limit Global Warming to 2° C or 1.5° C? A Preliminary Assessment" (Nairobi: United Nations Environment Programme).

Webster, M., A. Sokolov, J. Reilly, C. Forest, S. Paltsev, A. Schlosser, C. Wang, D. Kicklighter, M. Sarofim, J. Melillo, R. Prinn, and H. Jacoby, 2009, "Analysis of Climate Policy Targets Under Uncertainty" (Cambridge, Massachusetts: Massachusetts Institute of Technology, Joint Program on the Science and Policy of Global Change), available at http://globalchange.mit.edu/pubs/abstract.php?publication_id=1989.

This page intentionally left blank

CHAPTER

4 The Social Cost of Carbon: Valuing Carbon Reductions in Policy Analysis*

Charles Griffiths, Elizabeth Kopits, Alex Marten, Chris Moore, Steve Newbold, and Ann Wolverton
National Center for Environmental Economics, U.S. Environmental Protection Agency

Key Messages for Policymakers

- Without action to control rising greenhouse gases (GHGs), scientists predict that climate change will continue over time, bringing higher temperatures, sea level rise, and the potential for abrupt changes in earth system processes, with likely negative impacts on agricultural yields, ecosystems, human health, and more.
- These impacts are expected to vary widely over time and by geographic region, with developing countries likely to experience disproportionate damages due to limited adaptation opportunities and economic dependence on climate-sensitive sectors.
- The social cost of carbon (SCC) is the discounted monetary value of the future climate change damages due to one additional metric ton of carbon dioxide (CO_2) emissions.
- The U.S. government recently developed a set of SCC estimates for use in benefit-cost analyses of new regulations that influence CO_2 emissions—the central case estimate is $21 per tonne for emissions in the year 2010 (in 2007 U.S. dollars).
- Other countries could use these SCC estimates in benefit-cost analyses or to help set the initial level of a domestic carbon pricing policy, if those countries accept the policy judgments and methodological assumptions underlying the estimates.
- Other countries should consider developing their own SCC estimates when they wish to reflect fundamentally different assumptions, develop a long-term strategy to

* The views expressed in this chapter are those of the authors and do not necessarily represent those of the U.S. Environmental Protection Agency. We thank Joe Aldy, Terry Dinan, Robert Mendelsohn, Michael Keen, Ian Parry, and Tom Tietenberg for helpful comments and suggestions.

ED_442-001040137

evaluate emission reductions, or evaluate the cost-effectiveness of policies designed to meet a given long-term target.

- The SCC estimates should be updated over time to reflect changes in emissions, atmospheric concentrations, economic conditions, and advancements in scientific knowledge.

Greenhouse gas (GHG) emissions from human activities—mainly from the burning of fossil fuels, deforestation, and agricultural activities—are accumulating in the atmosphere and altering the earth's climate and other natural systems.[1] Between 1850 and 2005, the atmospheric concentration of carbon dioxide (CO_2), the predominant anthropogenic GHG, increased from about 280 to 380 parts per million (ppm). Along with increased atmospheric accumulation of other GHGs, this has significantly contributed to an estimated increase in the global average annual surface temperature of approximately 0.8° C above preindustrial levels. Rising temperatures are also causing the level of the oceans to rise—on average by about 20 cm during the twentieth century. In the absence of serious policy action to abate GHG emissions, atmospheric CO_2 concentrations are projected to continue rising, with the potential to increase the global average annual surface temperature by an additional 1.1° C to 6.4° C and the average sea level by an additional 20 to 60 cm by the end of this century. Even if atmospheric GHG concentrations were to be stabilized immediately at 2000 levels, scientists estimate that the average surface temperature would likely increase by an additional 0.3° C to 0.9° C by the end of the century due to a delayed response inherent in the climate system (see Chapter 3 for further discussion of emissions and climate trends). Temperature increases and changes in precipitation will not be uniformly distributed across the globe—the specific magnitude, direction, and spatial pattern of these changes are highly uncertain and are an area of ongoing scientific research.

In addition, the scientific literature has paid increasing attention to the likelihood and nature of potential "climate catastrophes"; that is, high-impact,

[1] Fossil fuel combustion contributes about 26 Gt of CO_2 a year, and land-use changes contribute another 6 Gt. Agricultural activities are the primary source of other potent GHGs such as methane and nitrous oxide. Figures cited in this chapter are from the Intergovernmental Panel on Climate Change's Working Group I, "Summary for Policymakers" (IPCC, 2007).

low-probability earth system changes due to rising GHG concentrations. Possibilities include the collapse of the Greenland or West Antarctic ice sheets, a shutdown or change in the Atlantic Ocean circulation, substantially altered periodic weather patterns, large releases of additional GHGs from methane deposits, massive dieback of tropical or boreal forests, and cascading effects in marine food webs from ocean acidification. However, research quantifying the magnitude and timing of the physical—and especially the economic—impacts from many of these potential risks is still in its infancy.

Current and anticipated climate changes are expected to have a wide range of mostly negative impacts on economies and societies across the globe, including (but not limited to) the inundation of coastal areas, reduced agricultural yields, and increased frequency and severity of tropical storms, droughts, and other extreme weather events. Recent studies suggest that a 2.5° C to 3.0° C increase in the average annual surface temperature above preindustrial levels will lead to aggregate annual damages of between 0 and 2.5 percent of global gross domestic product (GDP). These aggregate figures mask considerable disparity in regional effects. One study estimated damages from a 2.5° C increase in global average temperature ranging from a positive 0.7 percent of GDP for the former Soviet Union to a negative 5 percent of GDP for South Asia and India (Nordhaus and Boyer, 2000). Likewise, a recent assessment found that a global sea level rise of 0.5 m to 2 m could displace 72 to 187 million people over the twenty-first century (assuming no adaptation), about 70 percent of which would be concentrated in east, southeast, and south asia (Nicholls and others, 2011). Developing countries will likely experience larger than average damages due to limited adaptation opportunities, as well as greater dependence of their economies on climate-sensitive sectors like agriculture, although nations' vulnerability to climate change may diminish with economic growth over the coming centuries.

With the aid of integrated assessment models (IAMs) that combine simplified representations of the climate system, the global economy, and their interactions, analysts can evaluate the economic implications of GHG mitigation policies. In this chapter, we describe recent efforts by the U.S. government to estimate the social cost of carbon (SCC) to value the damages from small changes in CO_2 emissions for use in benefit-cost analysis of policies that directly or indirectly reduce GHG emissions. We then discuss the potential applicability of these estimates to policy analysis in other countries and regions. We close by highlighting areas of future research and the need for frequent reassessment of the SCC in light of new information.

The Social Cost of Carbon

Defining the SCC

Comparing the benefits of policies that result in carbon reductions to their economic costs requires a monetized measure for the value of future climate change damages. The SCC is one such measure. It is the present value of future damages associated with an incremental increase (by convention, 1 metric tonne) in CO_2 emissions in a particular year expressed in consumption equivalent terms. In theory, it is intended to be a comprehensive measure including, for example, damages from changes in agricultural productivity, human health risks, property damages from increased flood frequencies, and the loss of ecosystem services.

The SCC can be calculated from a global perspective, which incorporates damages to all countries caused by CO_2 emissions, or from a domestic perspective, which incorporates only the damages experienced by a country's own residents. The U.S. government interagency working group chose a global perspective to evaluate the SCC, mainly because climate change is a global externality (CO_2 emissions rapidly become well mixed in the atmosphere and therefore contribute to damages around the world no matter their source). The use of a global SCC is consistent with the goal of achieving a globally economically efficient solution. If nations were instead to design their policies independently using domestic SCC estimates (thereby excluding benefits that accrue to nonresidents), abatement would be meaningfully less than the globally economically efficient level.

Integrated Assessment Models

Estimation of the economic impacts of CO_2 emissions can be broken into four main steps: (1) projections of future GHG emissions, (2) the effects of past and future emissions on the climate system, (3) the impact of changes in climate on the physical and biological environment, and (4) the translation of these environmental impacts into economic damages, discounted back to the present. IAMs couple physical science and economic models to capture important interactions between these components. The IAMs most often used to estimate the SCC represent highly aggregated, reduced-form approaches. While other more comprehensive models, such as computable general equilibrium models, may better represent the complex interactions among sectors of the economy and trade flows among countries, they typically lack the links between physical impacts due to climate change and economic damages necessary for estimating the SCC.

Most of the published SCC estimates are derived from one of three IAMs: William Nordhaus' Dynamic Integrated Climate Economy (DICE) model, Richard Tol's Climate Framework for Uncertainty, Negotiation, and Distribution (FUND) model, and Chris Hope's Policy Analysis for the Greenhouse Effect (PAGE) model. Each model takes a somewhat different approach to translate changes in climate variables, such as temperature and sea level, into economic damages. Some of these differences arise from the model developers' choices about the level of aggregation across regions, the climate variables, and which damage categories are explicitly included in each model (see Box 4.1).

Box 4.1. Damages in the PAGE, DICE, and FUND Integrated Assessment Models

As summarized in Table 4.1, the three integrated assessment models (IAMs) used for estimating the social cost of carbon (SCC) vary in their treatment of damages. For instance, the Dynamic Integrated Climate Economy (DICE) model aggregates damages across sectors and regions into a single global damage function, while the Policy Analysis for the Greenhouse Effect (PAGE) model divides damages into economic and noneconomic categories. In contrast, the Climate Framework for Uncertainty, Negotiation, and Distribution (FUND) model separately calculates damages for 11 different market and nonmarket categories. DICE and PAGE also include categories that account for the possibility of large "catastrophic" damages at higher temperatures, while FUND does not. In DICE, parameters are handled deterministically and represented by fixed point estimates; in PAGE and FUND, most parameters are represented by probability distributions. Also, unlike PAGE, DICE and FUND treat GDP as endogenous so damages in early years reduce economic output in later years.

The economic damage estimates vary considerably across models at both lower and higher global average temperature changes. This reflects differences in assumptions about the rate of technological change, the ability of human and natural systems to adapt to the effects of climate change, and the projected vulnerability of developing countries, among others. For instance, FUND projects that climate change is potentially beneficial for a 2.5° C increase due to effects on agriculture and forestry and decreased heating costs. PAGE assumes that impacts occur only above some "tolerable" temperature increase, defined as 2° C for developed countries and 0°C in developing countries. Beyond the tolerable level, developed countries are able to eliminate almost all economic impacts through various adaptation measures (e.g., altering crop varieties or planting dates, building sea walls), while developing countries can eventually eliminate 50 percent of economic impacts through adaptation. Adaptation to noneconomic impacts (e.g., biodiversity loss) is much more difficult for both regions. DICE does not include explicit representation of adaptation,

Box 4.1. (*continued*)

Table 4.1. Summary of Climate Change Impacts by Category

Global Damages at 2.5° C Above Preindustrial Levels (Percent of global output)					
DICE 2007		**PAGE 2002**		**FUND 3.5**	
Agriculture	0.13	Economic impacts	0.36	Agriculture and forestry	–0.90
Coastal	0.32	Noneconomic impacts	0.65	Coastal	0.02
Other market sectors	0.05			Hurricanes and other storms	0.01
Health	0.10			Health	0.07
Nonmarket amenities	–0.29			Water resources	0.16
Human settlements and ecosystems	0.17			Biodiversity Loss	0.13
				Cooling	0.90
				Heating	–0.51
Subtotal:	*0.48*	*Subtotal:*	*1.01*	*Subtotal:*	*–0.13*
Catastrophes	1.02	Catastrophes	0.43		
Total	***1.50***	***Total***	***1.44***	***Total***	***–0.13***

Sources: Based on Hope (2006), Nordhaus and Boyer (2000), and Tol (2009).

Note: For general illustrative purposes only based on default assumptions in DICE 2007 (output-weighted damages) and deterministic runs of FUND 3.5 and PAGE 2002 using the mode values for all parameters. Damage categories are defined by model authors. Refer to documentation for each of the three models for more detailed information on how these are defined.

though some forms of adaptation—especially in the agricultural sector—are included implicitly through the choice of studies used to calibrate the aggregate damage function.

Source: Interagency Working Group on Social Cost of Carbon (2010).

While IAMs offer useful guidance about the effects of climate change on human well-being, modeling the complex systems involved often requires assumptions that cannot easily be verified based on historical evidence. For this reason, IAM results should not be interpreted as precise predictions of far future outcomes. This is well understood and is frequently emphasized by the IAM developers themselves, and IAMs are regularly updated as modelers revisit key aspects of their framework (e.g., damage functions, assumptions about adaptation, the representation of natural systems to reflect the evolving scientific and economic research).

SCC Estimates Used in U.S. Regulatory Impact Analysis

In 2009–10, the U.S. government formed an interagency working group to develop a set of SCC estimates to be used by all executive branch agencies to value reductions in CO_2 emissions in regulatory analyses. The purpose of this interagency working group was to improve the accuracy and consistency with which agencies value reductions in CO_2 emissions. Prior to this effort, SCC estimates were used in some but not all regulatory analyses, and the values employed varied substantially among agencies.

The interagency working group used the DICE, PAGE, and FUND models to estimate SCC values. The climate system submodels and the functions that map climate change to economic damages were left unchanged, but a common set of assumptions for three key inputs was used across all the models—socioeconomic and emissions projections, equilibrium climate sensitivity, and discount rates.

The interagency working group selected five scenarios of GDP, population, and GHG emissions projections from the 2009 Stanford Energy Modeling Forum exercise (EMF-22).[2] These scenarios spanned a range of emissions projections (including at least one case where the rest of the world takes significant action to reduce emissions) and plausible outcomes for future population and GDP. The motivation for this approach was to ensure that the GDP, population, and emission trajectories were internally consistent for each scenario considered. Across the five scenarios, atmospheric CO_2 concentrations in 2100 ranged from about 450 to 890 ppm (or 550 to 1130 ppm in CO_2 equivalent when other GHGs such as methane were included), the average percentage change in global per capita GDP ranged from 1.5 to 2.0 percent per year, and the percentage change in global population was 0.4 to 0.5 percent per year. Future projections of global GDP were based on combining regional GDPs using market exchange rates.[3]

[2] The socioeconomic scenarios are available at Stanford's Energy Modeling Forum, a group of well-regarded energy modeling teams from Asia, Australia, Europe, and North America. See: http://emf.stanford.edu/research/emf22/.

[3] While the EMF-22 models use market exchange rates (MER) to calculate global GDP, it is also possible to use purchasing power parity. Purchasing power parity takes into account that some countries consume very different baskets of goods, including domestically produced nontradable goods. MERs tend to make low-income countries appear poorer than they actually are. Because many models assume convergence in per capita income over time, use of MER-adjusted GDP gives rise to projections of higher economic growth in low-income countries. There is an ongoing debate about how much this will affect estimated climate impacts. Critics of the use of MER argue that it leads to overstated economic growth and hence significant upward bias in projections of GHG emissions and unrealistically high future temperatures. Others argue that convergence of the emissions-intensity gap across countries at least partially offsets the overstated income gap so that differences in exchange rates have less of an effect on emissions. Nordhaus argues that the ideal approach is to use purchasing power parity but recognizes the practical data limitations of doing so over long time periods, although he also notes that exchange rate conversion issues are probably far less important than uncertainties about population or technological change.

In reduced-form IAMs, the speed and magnitude of temperature change for a given emissions projection are strongly influenced by the equilibrium climate sensitivity (ECS) parameter, which represents the long-term climate response to atmospheric conditions that are similar to those that would be associated with an atmospheric CO_2 concentration of 550 ppm, ignoring all other relevant gases.[4] To represent the uncertainty of the responsiveness of the climate system to changing atmospheric conditions, the interagency working group used a probability distribution to represent ECS in all three models. The probability distribution was calibrated to the Intergovernmental Panel on Climate Change consensus statement about this parameter by applying three constraints—a median equal to 3° C, two-thirds probability that the ECS lies between 2 and 4.5° C, and zero probability that it is less than 0° C or greater than 10° C.[5]

Discount Rates Selected

Since the damages from a tonne of CO_2 emissions occur over many decades, the discount rate—which reflects the trade-off between present and future consumption—plays a critical role in estimating the SCC. For policies with both intragenerational and intergenerational effects, U.S. federal agencies traditionally employ constant real discount rates of 3 and 7 percent per year. However, discounting over very long time horizons raises exceedingly difficult questions of science, economics, philosophy, and law. Approaches for determining the discount rate for climate change analysis have been categorized as either "descriptive" or "prescriptive."

The descriptive approach is based on observations of people's actual behaviors, such as saving versus consumption decisions over time and allocations of investment among more and less risky assets. Advocates of this approach argue that because expenditures to mitigate GHGs are a form of investment, discount rates used to evaluate benefits from these expenditures should be based on market rates of return.

The prescriptive approach to discounting specifies a social welfare function that formalizes the normative judgments that the decision maker wants to incorporate into the policy evaluation; that is, how interpersonal comparisons

[4] Specifically, the ECS represents the increase in the annual global-average surface temperature from a sustained doubling of atmospheric CO_2 relative to preindustrial levels.

[5] The truncation at 10° C is reasonable considering the very long time lags associated with such high climate sensitivity values (i.e., such high temperature outcomes could only occur well beyond the relevant timeframe for policy analysis using the discount rates employed by the interagency working group).

of well-being should be made and how the well-being of future generations should be weighed against that of the present generation. Proponents of the prescriptive approach argue that various market imperfections (e.g., the absence of markets for very long-lived loans) make the market interest rate an unreliable measure of the appropriate trade-off between the consumption of present and future generations; instead, the discount rate should be specified partly based on ethical judgments about intergenerational equity. Often the rates recommended by the prescriptive approach are lower than those based on the descriptive approach.

The interagency working group drew on both approaches but relied primarily on the descriptive approach to inform the choice of discount rate. With recognition of its limitations, the interagency working group felt that this approach was the most defensible and transparent given its consistency with the standard principles of benefit-cost analysis. Regardless of the theoretical approach used to derive the appropriate discount rate(s), it is important to note the inherent conceptual and practical difficulties of adequately capturing consumption trade-offs over many decades or even centuries. In light of disagreement in the literature on the appropriate market interest rate to use in this context and uncertainty about how interest rates may change over time, the interagency working group used three constant discount rates—2.5, 3, and 5 percent per year—to span a plausible range.

Calculating the SCC

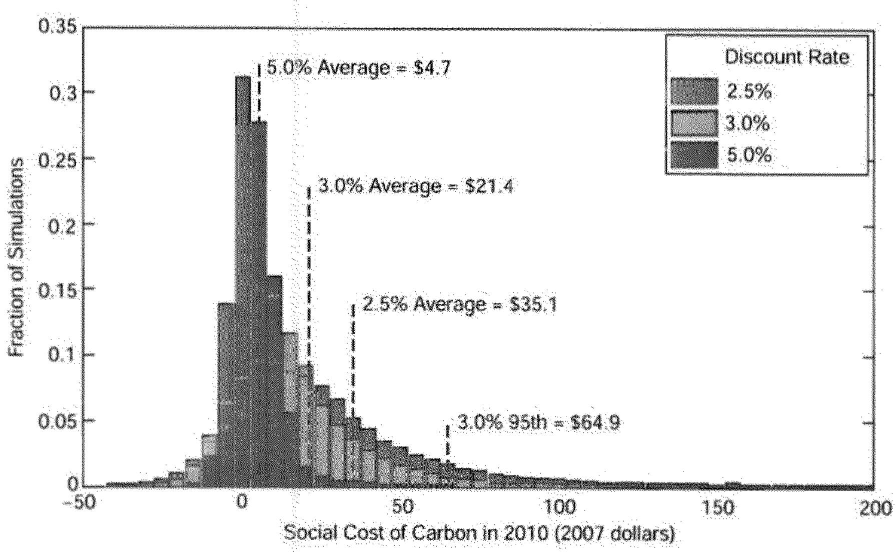
Four basic steps are required to calculate the SCC in a particular year *t*. First, each model is used to project paths of temperature change and aggregate consumption associated with the baseline path of emissions, GDP, and population. Second, each model is re-run with an additional unit of CO_2 emissions in year *t* to determine the projection of temperature changes and aggregate consumption in all years beyond *t* along this perturbed path of emissions. Third, the marginal damages in each year are calculated as the difference between the aggregate consumption computed in steps 1 and 2. Finally, the resulting path of marginal damages is discounted and summed to calculate the present value of the marginal damages in year *t*.

The steps above were repeated in each model for multiple future years to 2050. Because the climate sensitivity parameter is modeled probabilistically and because PAGE and FUND incorporate uncertainty in other model parameters, the final output from each model run represents a distribution over the SCC in each year. The exercise produced 45 separate distributions of the SCC for a given year, based on the three models, three discount rates, and five socioeconomic scenarios considered. To produce a range of estimates that reflects this uncertainty but still emphasizes the central tendency, the distributions from each of the models and scenarios were equally weighted and combined to produce three separate probability distributions for the SCC in a given year, one for each assumed discount rate.

Four SCC estimates were selected from these three probability distributions to reflect the global damages caused by one tonne of CO_2 emissions: $5, $21, $35, and $65 for 2010 emission reductions (in 2007 U.S. dollars). The first three estimates are based on the average SCC across the three models and five socioeconomic and emissions scenarios for the 5, 3, and 2.5 percent discount rates, respectively. The fourth value is the ninety-fifth percentile of the SCC distribution at a 3 percent discount rate and was chosen to represent potential higher-than-expected impacts from anthropogenic GHG emissions. Figure 4.1 illustrates where these values fall within the wider distribution of SCC values generated by the three IAMs at three different discount rates. Notice that the distribution is skewed toward high values of the SCC. The range of the distribution increases with lower values of the discount rate.

The SCC estimates also grow over time because future emissions are expected to produce larger incremental damages as the economy grows and physical and economic systems become more stressed in response to greater climatic change. These rates are determined endogenously by the models

Figure 4.1. Distribution of 2010 Social Cost of Carbon Values at Each Discount Rate



Source: Authors' calculations based on Interagency Working Group on Social Cost of Carbon (2010).

Table 4.2. Social Cost of Carbon, 2010–50 (In 2007 U.S. dollars per tonne of CO_2)

Year of Emission Reduction	Discount Rate			
	5 Percent Average	3 Percent Average	2.5 Percent Average	3 Percent 95th
2010	4.7	21.4	35.1	64.9
2015	5.7	23.8	38.4	72.8
2020	6.8	26.3	41.7	80.7
2030	9.7	32.8	50.0	100.0
2040	12.7	39.2	58.4	119.3
2050	15.7	44.9	65.0	136.2
Annualized percent change in SCC, 2010-50	3.1%	1.9%	1.6%	1.9%

Source: Modified from Interagency Working Group on Social Cost of Carbon (2010).

(see Table 4.2) and are dependent upon a number of assumptions including the socioeconomic and emissions scenario, model structure, parameter distributions, and the discount rate.

Having four estimates of the SCC raises the possibility that economic analyses of a single policy conducted with different values will generate different qualitative results. So, how should a policymaker interpret the results in such a case? In the United States, policymakers are asked to consider all four estimates of the SCC when conducting benefit-cost analysis, although the average values discounted at 3 percent are treated as central estimates. This is useful for purposes of informing decision makers of the robustness of a policy prescription to a range of values. It is also important to note that economic efficiency is only one of possibly many criteria U.S. policymakers consider when evaluating environmental policies. Furthermore, when there is substantial uncertainty surrounding the economic analysis, this may affect how much weight it is given relative to other criteria.

Using the Social Cost of Carbon for Policy Analysis

The appropriate role of the SCC in policy analysis and the applicability of the U.S. government's SCC estimates to analyses in other countries or regions depend on the nature of the policy in question, including the magnitude of the expected emission impact and timeframe of consideration. Because the SCC is the net present value of all future damages resulting from an additional tonne of CO_2 in year t, the estimates are conditional on forecasts of emissions and socioeconomic conditions from year t onward. Actions taken by the United States, or by other countries, to reduce emissions may change the forecasts of future damages. If these changes are large enough, then the future path of the SCC itself also would change. For this reason, the U.S. government's SCC estimates are most appropriate for analyzing policies that are expected to have a relatively small impact on global emissions and associated future climate conditions. To date, these values have been used to quantify the benefits of reducing CO_2 emissions from U.S. federal regulations such as energy efficiency standards for appliances and CO_2 tailpipe emission standards for light and medium heavy-duty vehicles. For long-term policies that have substantial impacts on global emissions, the appropriate SCC is one that accounts for the impact of the policy on forecasts of emissions and socioeconomic conditions.

Using the Social Cost of Carbon in Benefit-Cost Analysis

If policymakers in another country adopt the same set of policy judgments and methodological assumptions used by the U.S. government, then they can directly apply the SCC values described here to calculate monetized global benefits of CO_2 reductions resulting from domestic policies. The only adjustments needed involve translating the SCC estimates into the currency of the country where the analysis is to be conducted to allow for direct comparison to the domestic costs and other monetized benefits. In a developing country with a substantial portion of its economy made up of nontraded sectors, the market exchange rate may not provide an accurate assessment of what actions are worth taking, particularly when the SCC is being compared to domestic costs.[6] However, given that the SCC values estimated by the U.S. interagency working group are based on global GDP projections that use market exchange rates and the uncertainty involved in projecting purchasing power parity many years into the future, using market exchange rates is likely simpler and more transparent.

If policymakers in another country want to adopt other policy judgments or methodological assumptions, then the SCC estimates would need to be recalculated accordingly. Revised estimates could accommodate a variety of policy and ethical considerations, such as the use of a lower discount rate, used of a domestic SCC value, and equity weighting. We will now briefly discuss each consideration.

Discount Rates

While the interagency working group chose to use three different constant discount rates, other rates may also be consistent with what has been used

[6] This is not the case if a country uses the SCC values to approximate the level of a "global" carbon price. In this case, the ultimate objective of a social planner would be to maximize global benefits minus global costs. Any payments made across countries for emission reductions would occur at the market exchange rate.

in the literature. For instance, some decision makers may prefer to select a discount rate that reflects the prescriptive approach or a higher aversion to climate risks. Alternatively, they may want to use a nonconstant or declining rate to reflect greater uncertainty further into the future. If a different discount rate is desired to calculate the present value of avoided damages from one tonne of CO_2 emissions, then an entirely new set of SCC values must be generated. In general, use of a lower discount rate will result in a higher average SCC value. Incorporating uncertainty in the discount rate is also expected to increase the average SCC value relative to the equivalent constant discount rate (see Box 4.2 for a more detailed discussion of discount rate uncertainty).

Box 4.2. Treating Uncertainty in the Discount Rate over Long Time Horizons

While the U.S. interagency working group used a range of constant discount rates to generate SCC estimates, there is empirical and theoretical support for using a schedule of discount rates that declines over time. A number of studies in this area have found that uncertainty about future discount rates can have a large effect on net present value. A main result from these studies is that if there is a persistent element to the uncertainty in the discount rate, the effective discount rate declines over time. Consequently, lower discount rates tend to dominate the present value calculation over the very long term.

The proper way to model discount rate uncertainty remains an active area of research. One approach is to employ a model of how long-term interest rates change over time to forecast future discount rates. This type of model incorporates some of the basic features of how interest rates move over time, and its parameters are estimated based on historical observations of long-term rates. Subsequent work on this topic uses more general models of interest rate dynamics to allow for better forecasts that account for the present level of interest rates and the persistence of shocks. A simplified alternative to formally modeling uncertainty in the discount rate is to use a schedule of discount rates as has been done in both the United Kingdom and France. In this case, the analyst would apply a higher discount rate over the first 40 to 50 years of the policy and a graduated schedule of lower discount rates further out in time.

Source: Interagency Working Group on Social Cost of Carbon (2010).

Domestic SCC Values

Likewise, if policymakers wish to limit the analysis to a comparison of domestic benefits and costs, then the SCC values would need to be adjusted to exclude all damages experienced by residents of other nations. It is worth noting, however, that if each nation used an SCC estimate that included only its own domestic damages to evaluate regulations, then the result would be a much lower level of abatement in each country. Furthermore, the global level of abatement that would be realized under this scenario could be achieved at a lower cost if all countries used a common SCC value (or if international trading for emission rights was allowed) since marginal abatement costs would then be equalized across regulated sources.

Equity Weighting

Policymakers also may want to conduct a global social welfare analysis (using an explicit social welfare function that weighs both efficiency and distributional concerns) rather than, or in addition to, a benefit-cost analysis (which typically addresses economic efficiency alone). The SCC estimates developed by the U.S. interagency working group reflect an explicit decision to focus only on economic efficiency, which counts the willingness-to-pay of all individuals who will be affected by climate change equally, no matter their country of residence or income. It is possible to incorporate equity weights that adjust the measure of economic damages for differences in incomes among the affected individuals, but the SCC would need to be recalculated. In such an analysis, the monetized costs of the policy also would need to be adjusted using the same set of equity weights. In Box 4.3, we provide a brief perspective on the use of the SCC in other countries.

Box 4.3. An Illustration of Use of the SCC for Decision Making in Other Countries

The United States is not the only country that has developed social cost of carbon values. The United Kingdom first recommended the use of the SCC for informing national policies on GHG emissions in 2002 and commissioned a series of reports to examine the issue. The most widely known of these reports is the Stern Review. The SCC values estimated by Stern differ from the values used by the U.S. government in a number of ways. For example, Stern uses a lower discount rate and includes equity weighting. Relying on input provided by the Stern Review, the UK government officially set a value for the SCC in 2007 for the express purpose of determining the most appropriate limit on CO_2 emissions (referred to as a stabilization target when expressed in terms of the carbon concentration in the atmosphere). This value was set at about $50 per tonne of CO_2 equivalent in terms of 2007 U.S. dollars (i.e., £25.5 per tonne), rising at a rate of 2 percent annually. Germany followed the United Kingdom's

Box 4.3. (*continued*)

lead, relying on the same SCC value to evaluate its own domestic carbon policies, but suggesting sensitivity analysis using, in U.S. dollar terms, $15 and $215 per tonne.

In 2009, the United Kingdom moved away from using an SCC approach. It stated two reasons for this: (1) The SCC requires assumptions about what other countries will do to reduce GHGs and (2) there is a large degree of uncertainty around SCC estimates. In its place, the UK government now uses a shadow price of carbon for policy evaluation. It has two different sets of values, one to assess policies that reduce traded carbon emissions under the European Union's cap-and-trade policy and another to assess the cost-effectiveness of reducing GHGs in nontraded sectors of the economy.

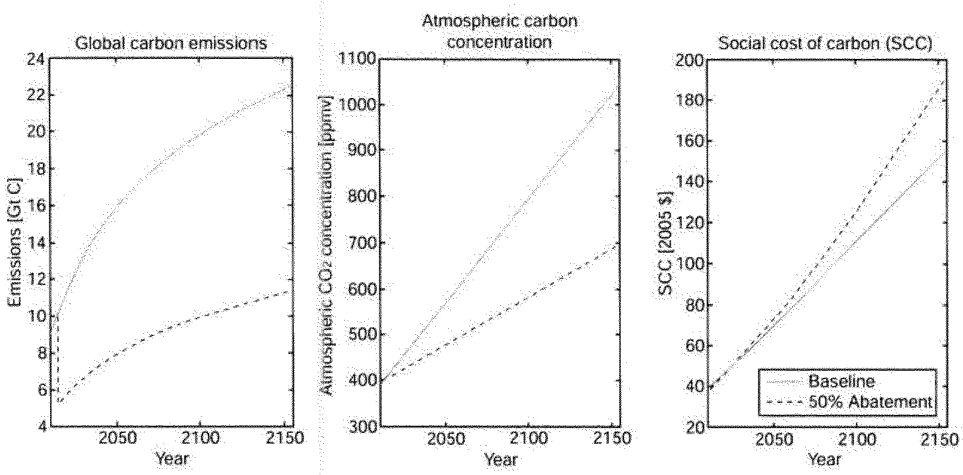
Sources: DECC (2009); Umwelt Bundes Amt (2008).

SCC and Carbon Taxes

A country or group of countries may also be interested in using the SCC to help set the level of a carbon tax. However, it is important to note that the U.S. government's SCC values were calculated along a business-as-usual emissions path, not a socially optimal one. Therefore, countries should avoid locking in a long-term tax policy using the U.S. government's schedule of SCC estimates given in Table 4.2. Instead, the carbon tax in the near term should be set equal to the current best estimate of the global SCC and then adjusted over time to match an SCC that is reestimated as sources adopt new measures to reduce their emissions. Economic efficiency is achieved when the marginal abatement costs are equalized across all sources and are in turn equal to the current updated SCC.

In theory, a global carbon tax could be imposed at the outset without the need for adjusting the tax schedule over time, but only if the ultimate globally economically efficient level of emissions could be determined at the beginning. However, it should be noted that in the short run, the marginal benefit curve is relatively flat for CO_2 emission reductions because of the time lag inherent in the climate system and the relatively flat relationship between damages and climate change at relatively small temperature changes. This means that even for a nonmarginal tax policy, the SCC will not differ much from the marginal policy path in the near term. Figure 4.2 illustrates this point by showing the time path of the SCC along two separate emissions trajectories using the DICE 2010 model. The first represents a business-as-usual scenario. The second represents a large policy change, specifically a 50 percent reduction in CO_2 emissions each year relative to the business-as-usual path.

Figure 4.2. Social Cost of Carbon Values for Business-as-Usual and Nonmarginal Policy Emissions Paths



Source: Authors' calculations based on the DICE model.

Note: This example uses a constant consumption discount rate of 3 percent per year, but all remaining parameters are based on the default values in DICE 2010.

Notice that the SCC values for the two scenarios are very close to each other in the early years of the forecast: The SCC on the policy path remains within 5 percent of the SCC on the business-as-usual path for at least the first 45 years, even though the emissions on the policy path are 50 percent lower than those on the business-as-usual path starting immediately after the first time period. This is an extreme example, but it effectively demonstrates that it would be reasonable to use the SCC estimated along a business-as-usual forecast as a guide for setting a domestic carbon tax in the near term, such as in the next 10 to 20 years.[7]

Social Cost of Carbon and Cost-Effectiveness

The SCC is not the appropriate measure for evaluating projects when the overall policy objective is to meet a predetermined emissions (or concentration or temperature) target at the lowest possible cost. If the environmental target is specified ex ante, then a measure of the benefits

[7] Also note that in this example, the SCC increases when emissions are reduced. One reason this occurs is that in the DICE model, climate damages are represented as the loss of a fraction of gross economic output in each period, where the fraction of output lost depends only on the temperature anomaly in the period. Economic output net of climate damages is allocated to consumption and investment, so reduced damages in early periods can lead to increased economic output, and therefore increased absolute damages, in later periods.

of abatement is not needed. Instead, a measure of the marginal cost of abatement—sometimes called the "shadow price of carbon"—can be used to evaluate the cost-effectiveness of the policy (see Box 4.3). The two measures will be equal only when the emissions target is set at the economically efficient level.

Caveats and Reassessing the Social Cost of Carbon in the Future

The SCC estimates developed by the U.S. federal government for use in a benefit-cost analysis are subject to several important caveats. They are based on a number of assumptions and modeling simplifications that are not readily verifiable in the real world. For instance, there are many differences across the IAMs in how damages are modeled, as well as the treatment of technological change, adaptation, and catastrophic damages. Gaps in the literature make modifying these aspects of the models challenging, which highlights the need for additional research. Other key areas for future research include improvements in how predicted physical impacts translate into economic damages for a wide range of market and nonmarket damage categories, better incorporation of sectoral and regional interactions, the treatment of the discount rate in regulatory analyses where costs and benefits are widely separated in time (including how to address uncertainty), and methods for estimating the marginal damages from non-CO_2 GHG emissions.

In addition, the SCC estimates are based on a range of socioeconomic scenarios for how emissions will develop over time. As technologies develop, populations and economies grow, and countries formulate policies to reduce emissions, it is a virtual certainty that reality will diverge from what was assumed in the models to estimate the SCC. Thus, to keep pace with new research developments and to reflect diverging long-term trends, the SCC values should be reestimated on a regular basis.

Finally, it is worth emphasizing that attempts to estimate the SCC involve many unquantifiable uncertainties inherent to forecasting complex systems far into the future. This is due to the difficulty in accurately representing the many linkages between natural and economic systems as well as unforeseeable changes in population growth, technological progress, and regional economic growth. Therefore, the results from IAMs such as those discussed in this chapter should not be viewed as highly precise estimates of the SCC—or even precise estimates of the probability distribution over the SCC. Nevertheless, such models still provide invaluable information for policy analysis by quantifying what is currently known about potential climate damages and by providing a rigorous basis from which decision makers can assess the potential implications of the unavoidable modeling simplifications and omissions.

References and Suggested Reading

For background on climate trends and the science of global warming, see the following:

Intergovernmental Panel on Climate Change, 2007, "Summary for Policymakers," in *Climate Change 2007: The Physical Science Basis.* Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. (Cambridge, UK: Cambridge University Press).

On sea level rise specifically, see the following:

Nicholls, Robert J., Natasha Marinova, Jason A. Lowe, Sally Brown, Pier Vellinga, Diogo de Gusmão, Jochen Hinkel, and Richard S. J. Tol, 2011, "Sea-Level Rise and Its Possible Impacts Given a 'Beyond 4°C World' in the Twenty-First Century," *Philosophical Transactions of the Royal Society A*, Vol. 369, No. 1934, pp. 161–181. DOI: 10.1098/rsta.2010.0291.

For some discussion on the valuation of climate change damages and the social cost of carbon, see the following:

ICF International, 2011a, *Improving the Assessment and Valuation of Climate Change Impacts for Policy and Regulatory Analysis: U.S. EPA/DOE Workshop Summary Report. Part I: Modeling Climate Change Impacts and Associated Economic Damages*, http://yosemite.epa.gov/ee/epa/eerm.nsf/vwRepNumLookup/EE-0564?OpenDocument.

ICF International, 2011b, *Improving the Assessment and Valuation of Climate Change Impacts for Policy and Regulatory Analysis: U.S. EPA/DOE Workshop Summary Report. Part II: Research on Climate Change Impacts and Associated Economic Damages*, http://yosemite.epa.gov/ee/epa/eerm.nsf/vwRepNumLookup/EE-0566?OpenDocument.

Interagency Working Group on Social Cost of Carbon, 2010, *Social Cost of Carbon for Regulatory Impact Analysis under Executive Order 12866*, February, http://www.whitehouse.gov/sites/default/files/omb/inforeg/for-agencies/Social-Cost-of-Carbon-for-RIA.pdf.

National Research Council, 2009, *Hidden Costs of Energy: Unpriced Consequences of Energy Production and Use* (Washington: National Academies Press).

For more detail on the integrated assessment models used in the U.S. interagency working group report on social cost of carbon, see the following:

Hope, Chris, 2006, "The Marginal Impact of CO_2 from PAGE 2002: An Integrated Assessment Model Incorporating the IPCC's Five Reasons for Concern," *The Integrated Assessment Journal,* Vol. 6, No. 1, pp. 19–56.

Nordhaus, William, and Joseph Boyer, 2000, *Warming the World: Economic Models of Global Warming* (Cambridge, Massachusetts: MIT Press).

Tol, Richard, 2009, "An Analysis of Mitigation as a Response to Climate Change" (Copenhagen: Copenhagen Consensus on Climate).

For perspectives on discounting climate damages, see the following:
Portney, Paul, and John Weyant, eds., 1999, *Discounting and Intergenerational Equity* (Washington: Resources for the Future Press).

For other country perspectives on the SCC, see the following:
DECC, 2009, *Carbon Valuation in U.K. Policy Appraisal: A Revised Approach* (London: Department of Energy and Climate Change).

Umwelt Bundes Amt, 2008, *Economic Valuation of Environmental Damage: Methodological Convention for Estimates of Environmental Externalities* (Dessau-Rosslau, Germany: Federal Environment Agency).

This page intentionally left blank

CHAPTER

5 Forest Carbon Sequestration*

Robert Mendelsohn
Yale University, United States

Roger Sedjo
Resources for the Future, United States

Brent Sohngen
Ohio State University, United States

Key Messages for Policymakers

- An efficient forest carbon sequestration program could account for about a quarter of the desired global carbon dioxide (CO_2) mitigation over this century (with most of the remaining 75 percent from reducing carbon emissions from fossil fuels). An estimated 42 percent of this carbon storage could be achieved via reduced deforestation, 31 percent from forest management, and 27 percent from afforestation, with about 70 percent of overall carbon sequestration occurring in tropical regions.

- A serious deficiency in current sequestration programs is that each project is asked to prove additionality. However, it is not straightforward to identify which hectares are marginal and which would have stored carbon regardless. An administrative alternative is to establish a baseline level of carbon for forests in each country. Fees would then be charged for any reductions below the baseline and subsidies for carbon storage above the baseline. Setting the baseline equal to the existing level of carbon would lead to subsidies only for additional storage.

- Scaling-up small projects to promote forest carbon sequestration will be difficult given limited technical capacity and leakage. National programs are likely easier to administer.

* We thank Stephane Hallegatte, Alex Martin, Adele Morris, Sergey Paltsev, and Andrew Stocking for helpful comments and suggestions.

- National programs also allow national governments flexibility to address local institutions and property rights such as overlapping claims to timber, grazing, fuel wood, and nontimber forest products from the same forests.
- Measuring sequestered carbon can be problematic. Monitoring and enforcement is critical to maintain incentives for long-term storage. International agreements should encourage inexpensive monitoring technologies to keep these costs limited.
- The design of incentives is critical. For example, using forest coverage as a proxy for carbon storage provides no incentive to increase carbon per hectare. Similarly, lump sum payments for carbon give no incentive to protect established forests. Annual payments for the annual value of stored carbon encourage continued efforts to safeguard standing carbon.

Over a trillion tonnes of carbon dioxide (CO_2) are currently stored in biomass in the world's forests. Even without a carbon sequestration policy, forests appear to be sequestering an additional 4 billion tonnes of CO_2 per year. This net gain of 4 billion tonnes comes from a gross gain of 10 billion tonnes through forest planting and growth minus 6 billion tonnes of CO_2 lost from tropical deforestation each year. Some of this deforestation is harvesting for forest management, but a great deal of it is land conversion to agriculture. If one examines just the lost carbon from deforestation, forestry/land use causes 15 percent of man-made emissions. However, carbon cycle measurements confirm that forests are likely the sink for the 4 billion tonnes of "missing carbon." Whether forests can continue to be a sink depends upon the future effect of CO_2 fertilization and climate change on forest carbon stocks.

The key policy issue is not the baseline land-use emissions but rather what policy can do to increase carbon sequestration in forests. The Kyoto Protocol includes specific mechanisms to try to increase the stock of carbon in forests (Kyoto Protocol, Article 3.3). First, carbon storage can be increased by reducing deforestation. For example, the Forest Carbon Partnership Facility at the World Bank has developed a fund of about $400 million (World Bank, 2011) to reduce carbon emissions from deforestation. Second, carbon can be increased by planting trees in areas that are no longer forested (afforestation). Third, carbon storage can be enhanced by increasing forest intensity with plantations, fertilizer, or forest management.

How much additional carbon can be stored in forests depends on two things—what society is willing to spend to store more carbon and how quickly the carbon must be stored. The more rapidly carbon must be stored, the more expensive it is. A number of literature reviews have now shown that it may be possible to increase carbon in forests by about 4 billion tonnes CO_2

per year with a price per tonne of CO_2 of up to US$30 (in current dollars). This level of sequestration essentially doubles the net natural sequestration that is already occurring. Starting with an efficient price path for CO_2 from an integrated assessment model, an efficient universal program of forest carbon sequestration could account for 25 percent of all carbon mitigation (energy would be responsible for the bulk of the remaining mitigation). Many economic studies of carbon sequestration, however, have not addressed important administrative hurdles that a global program will have to face. Some of these, listed as follows, could be managed by carefully designing the sequestration program.

- "Leakage" can dramatically reduce the effectiveness of carbon sequestration if the program is not consistent across sites and is not universal.

- The process of storing carbon in forests is dynamic because it takes time for trees to grow and because the price of carbon changes over time. The sequestration instrument must be able to capture these dynamic properties.

- There are potential measurement and verification issues that need to be overcome to ensure that forests are being properly managed over time.

- Historically, carbon mitigation programs have tried not to pay for forest activities that might have been done anyway, and so they have been burdened by proving "additionality."

The following are also some problems that simply have not yet been addressed.

- Most analyses assume that forest carbon sequestration projects can be easily and quickly scaled-up from a few limited experiments to a globally comprehensive program with modest institutional costs.

- Forest ownership is often complex, especially in tropical countries. Many owners often have legitimate overlying claims on different forest amenities on the same piece of land.

- There are equity issues concerning who will be compensated by any carbon sequestration scheme.

We start this chapter by reviewing the potential of carbon sequestration in forests. The evidence suggests that forest sequestration is potentially an important source of mitigation. We then shift our focus to the administrative hurdles that must still be overcome to take advantage of carbon sequestration in forests.

Finally, we discuss the measurement and monitoring problems and the feasibility of scaling-up forest carbon sequestration globally in light of these complexities.

The Potential of Carbon Sequestration

Although some visionaries call for forests to be planted in deserts and other hostile locations, only a fraction of land is hospitable to forests. Growing forests in places without adequate soil and water would be prohibitively costly.

On lands that can support forests naturally, carbon sequestration can be achieved via three basic forestry activities—afforestation, forest management, and avoided deforestation. Afforestation involves converting former agricultural and abandoned crop lands back into forests. In areas where forests are most productive (i.e., moist tropical regions), they can sequester up to 11 tonnes of CO_2 per hectare per year in above-ground biomass and additional carbon below ground. Up to 2 billion hectares of forests have previously been deforested and converted to agriculture worldwide. All of this land could potentially be converted back to forests. Of course, this would leave us with little agricultural land. There is consequently a trade-off between forestland and agricultural land. The more land that is converted back to forestland, the higher the opportunity cost will be (from lost farmland). And carbon saved from afforestation takes a long time to be stored as it takes decades for trees to grow large enough to store substantial amounts of carbon.

Reducing emissions from deforestation is more promising. According to the Food and Agricultural Organization (FAO), an additional 6 million hectares of deforestation occurs each year globally, with most of the gross changes occurring in the tropics. Mature tropical forests contain a large stock of carbon per hectare (300 to 400 tonnes CO_2 per hectare). In the case of many tropical countries, a great deal of this stock is burned to prepare land for pasture or farming and therefore leads to a vast amount of immediate carbon emissions.

It is also possible to increase carbon in forests by changing forest management. According to the FAO, over 1 billion hectares of forests globally are currently production forests, but only 70 to 100 million hectares of forest are fast-growing plantations. Converting more forestland to plantations could quickly increase carbon sequestration. Additional potential management actions include postponing timber harvests, tree planting rather than natural regeneration, thinning to increase forest growth, fighting forest fires and other disturbances, and fertilizing.

If forest owners were paid US$30 per tonne of CO_2 permanently stored, they would be willing to sequester about 4 billion tonnes of additional CO_2

in forests each year. In an efficient program, approximately 42 percent of this carbon storage could be achieved via reduced deforestation, 31 percent via forest management, and 27 percent via afforestation. Afforestation accounts for relatively little of the additional carbon storage because it takes a long time for young forests to actually accumulate carbon and because the opportunity cost of forestland is high. In an efficient program, about 70 percent of carbon sequestration should occur in tropical regions (developing economies). Globally, 20 countries contain over 80 percent of the world's forest carbon. This group includes the five largest carbon-storing countries (Brazil, Canada, the Democratic Republic of Congo, Russia, and the United States) as well as Indonesia, Malaysia, and other countries in South America and Africa that are responsible for most of the global deforestation.

If forest owners were paid significantly more than US$30 per tonne of CO_2, they would be willing to store even more carbon. It is also true that forests could store more carbon if given more time. With more time, programs such as afforestation become increasingly effective. By 2100, for example, approximately 367 billion tonnes of CO_2 could be stored in forests cumulatively with a final price of US$50 per tonne CO_2, providing about 25 percent of the cumulative abatement over this period. With a price of US$110 per tonne CO_2, over 1.4 trillion tonnes could be stored by 2100 (Sathaye and others, 2006).

Institutional Hurdles

Scaling-Up

There are a host of small programs and case studies that have tried to reduce deforestation and increase afforestation in order to capture carbon in forests. Can these small projects easily be scaled-up to a global program in a decade? Past experience suggests that it is often very difficult to scale-up small experiments to even a national level, much less a global level. The experts and volunteer (nongovernmental) organizations that support all of these small-scale efforts are not sufficient to manage a global program. The program would have to expand to between 1,000 and 10,000 times its current size. The existing capacity could not manage such a vast increase. Many more people would have to be trained in forestry. It would take time and resources to increase the scale of current efforts.

Of course, scaling-up may be easier in some countries or regions than others. For example, the U.S. Conservation Reserve Program (CRP), which sets aside farmland in the United States for environmental protection, scaled up from 0 to over 12 million hectares in 5 years (U.S. Department of Agriculture, Farm Services Agency). The current administrative cost of the CRP is about $7 per hectare of land enrolled. This includes costs of administering the contracts and verifying that the practices are still in place in the 10–15 years of the contract length.

Although the CRP shows that it is possible in some circumstances to scale-up environmental protection programs relatively quickly, there were many complaints early on that the program did not pay full attention to environmental (primarily conservation) benefits. Many lands enrolled in the initial stages were low-value croplands in regions far from human population where the environmental benefits were less valuable. In addition, this program was conducted in the United States where land ownership is usually fairly easy to prove. An enlarged global forestry carbon program would require substantial attention be paid to the benefits of the program, and it would probably require clear titles to be obtained in regions where ownership may be disputed. These factors could make the program difficult to implement in many regions.

Dynamics

There are two reasons that a carbon sequestration program should be dynamic. First, the marginal benefit of carbon storage (social cost of carbon [SCC]) is the damage avoided by permanently sequestering a tonne of carbon. This marginal value increases over time as greenhouse gas concentrations rise. Consequently, the marginal cost of carbon sequestration programs should also rise over time as the marginal benefit rises. This makes the carbon sequestration program inherently dynamic, with more carbon being stored over time. Second, trees grow according to a sigmoid growth function (growth increases with age up to a maximum and then it decreases with age). Trees do not grow at a constant rate. Afforestation and forest management programs generate different amounts of carbon storage over time.

One way that carbon sequestration programs can be accurately tied to what each forest can provide is to rely on rental payments for annual carbon storage (rather than one-time payments for permanent storage; see, for example, Marland, Fruit, and Sedjo, 2001; and Sedjo and Marland, 2003). Using annual payments also provides a continued incentive for the forest owner to protect the forest. This is lost once an up-front lump-sum payment is made. Rental payments should equal the SCC (the present value of the stream of marginal damage caused by a tonne of carbon) times the interest rate. For example, with a real interest rate of 4 percent, the rental payment for an SCC of US$30 per tonne of CO_2 is equal to US$1.20 per tonne per year ($30 times 0.04).

Measurement

Measurements of forestlands and timber volumes have been under development for decades. For example, the U.S. Forest Service samples sites across the 700 million acres of U.S. forest every 5 years (although the exact sampling regimen varies by state). These ground measurements are then supplemented with aerial and remote sensing information. The FAO estimates global forest areas by country. Unfortunately, the quality of the data varies greatly across countries, so there is considerable uncertainty around their estimates. The total amount of land in forests is somewhat uncertain because there is a complicated edge between forested savannah and fully grown forests. However, the biggest uncertainty concerns the stocking per hectare of forests (the amount of carbon per hectare). This can vary by land productivity, by species, and by land management. For example, the annual sequestration rate for a typical New England forest is 0.5 tonnes per hectare per year, a southern pine plantation is 1 tonne, and a moist tropical forest could be as high as 11 tonnes.

It is somewhat easier to verify whether an acre of intact forest has been clear-cut. Satellite pictures over time can reveal dramatic changes in land cover such as a clear-cut. However, what is more difficult to verify is the biomass per hectare of forested land. The actual biomass is important because selective harvesting can reduce biomass without causing visible clear-cuts. Further, intensive forest management can increase biomass, but again, this is not visible to a satellite. Verification of the biomass per hectare in forests may require ground-truthing, which is very expensive. Current estimates of the monitoring costs of the U.S. system are $72 million per year, or $0.24 per hectare. The annual change in carbon in above-ground stocks is about 635 million tonnes of CO_2 per year, so the cost of measuring a change in carbon in forests in the United States is about $0.11 per tonne CO_2. This is relatively high compared to the annual value of a tonne of carbon storage, which is less than $1.20 per tonne.

The cost of monitoring is even higher with small isolated projects. Specific projects for smaller areas of 1,000 to 600,000 hectares could cost US$1 to US$2 per tonne CO_2 (see Antinori and Sathaye, 2007; and Antle and others, 2003). Measuring and monitoring regimens could be done every 5 years to keep these costs down. Measuring just above-ground carbon (usually about three-fourths of the total carbon) could also keep costs down. Some new promising technologies, such as Light Detection and Ranging (LIDAR), that rely on low-level aerial photography can estimate wood volumes much more cheaply than ground-truthing. However, the carbon content depends upon weight, not volume, and hence some activities in addition to LIDAR are required.

Additionality

The total cost of the carbon sequestration program depends not only on the price of carbon (rental rate per year), but also upon what carbon must be purchased. The simplest program to administer is to pay every forest owner the rental rate on every tonne of carbon stored. For example, if the rental rate is US$0.60 per tonne per year and there are 1 trillion tonnes of carbon stored in forests, that would involve a payment of US$60 billion per year every year. However, many architects of carbon policy wish to pay just for the additional carbon stored (not the baseline that would have been stored anyway). If a program stored 4 billion additional tonnes, that would require an annual payment of just US$0.024 billion. Only the additional tonnes would be paid for. Of course, this raises the intriguing question of what tonne is additional versus baseline. In practice, this is very difficult to determine, and past case study projects have been handicapped by proving additionality. It is very difficult for a project to prove what would have happened anyway and what will now happen with a carbon sequestration program. Would there, in fact, be a change in behavior because of the program or is there an incentive for every forest owner to simply claim it? It is very hard to identify the actions that are on the margin.

Other ways to avoid this problem with additionality involve switching the property rights. The rental methods described above assume that landowners or land managers have the right to sell carbon credits onto markets. The current policy discussion embraces this property right. However, society could instead decide to treat forests as a potential emission source and tax carbon emissions. A carbon tax at the time of timber harvest combined with a subsidy for annual growth would have the same overall economic costs as the carbon rental scheme described above, but it would not require society to determine additionality with each carbon project. A carbon tax and subsidy scheme would change the distribution of carbon payments, but it would not require spending resources to prove additionality. Of course, taxing forest owners for releases of carbon from their forests suddenly makes forests a liability. If not carefully handled, this could create perverse incentives for reducing forests even further prior to program implementation.

Leakage

Economic analyses of land use suggest a carbon storage program must be universal to be effective. Of particular concern is the global trade-off between forestland and farmland. If some lands are in the carbon storage program and some are not, the scarcity that the program lands create for farmland encourages non-program lands to convert forests to farming. This phenomenon is called leakage. It can dramatically reduce the effectiveness of the carbon storage program. For example, a reduction of timber harvests in one region may simply result in an increase in the market price and increased harvests elsewhere, either within the country but also perhaps beyond its boundaries. Also, suppose one set of countries joins the program and sets aside an additional 50 million hectares of land for carbon storage by converting farmland to forestland. This would dramatically increase the scarcity of farmland and create a huge incentive for the countries not in the program to convert their forestland to farmland. Depending on how substitutable the land might be, the nonparticipating countries could actually convert 50 million hectares of forestland to farmland in response to the incentives created by the program, making the carbon storage program completely ineffectual. Although this is a worst case scenario, the problem of leakage is not trivial.

One solution to leakage is a universal program. If all land everywhere faces the same incentive to store carbon, there would be no leakage. The carbon storage program does not technically have to be identical in every country. Some countries might use regulations or taxes, whereas other countries might be inclined to use subsidies and tax breaks. However, all of the programs must use the same effective marginal incentive to store carbon; otherwise, the leakage problem will reduce the effectiveness of the global effort. Of course, what is important is that most of the potential forestlands in the world face the same incentive. Therefore, what is really important is to have agreement across the countries with most of the world's forest. If the agreement could cover the 20 countries with the most forest in the world, about 80 percent of forests would be covered.

Some researchers have proposed discount factors to correct for potential leakage. Discount factors work by requiring suppliers of carbon credits to provide additional carbon for each credit claimed. For instance, if the discount factor is 2, a country would have to provide 2 units of carbon credits for each 1 unit that receives a payment. Discount factors penalize countries that engage in carbon sequestration by giving them rights to only a certain percentage of the carbon they could store, thus reducing the value of their carbon stock. Discounting for leakage raises costs arbitrarily, gives incentives for countries to remain out of the program, and creates other inefficiencies. When designing a carbon system, it is preferable to include elements that provide incentives for new countries to enter into the system and not for them to stay out of the system.

Permanence

The question of permanence arises because forests store carbon only temporarily, while the tonnes of carbon released into the atmosphere by energy processes are "permanently" added to the atmosphere. Forests planted expressly for carbon sequestration, for instance, will sequester and hold carbon only so long as they remain standing. There is some probability that forests will be affected by fires, pests, windstorms, human-directed harvesting, or any number of other natural or human factors. As a result of the "impermanence" of forests, many researchers have suggested discounting carbon credits, similar to what is proposed with leakage. A number of prominent voluntary carbon standards have now taken this approach (e.g., the Verified Carbon Standard).

As in the case of leakage, when ad hoc discounts are used, inefficiencies are created. The inefficiency is particularly problematic with permanence, however, because rental contracts, as we have discussed, provide a clear alternative. Rental contracts pay for temporary carbon storage. If forests are not permanently maintained, then rental payments would stop. As long as the buyer is liable for ensuring that the carbon credits are offset somehow, the buyer can go onto the market and buy new credits or rent new forests.

Forest Ownership

Another complexity that must be overcome to create a global program involves overlapping forest ownership. In many forests in the developed world, forests are owned privately by an individual or firm. Most carbon storage programs imagine that they must deal with only a single owner. However, even in developed economies, a great deal of forest is owned by the government or held in some type of common ownership. Here there may be many interest groups that cherish very different aspects of the same forest. A program that encourages more carbon in the forest would enhance some of those services but threaten others. For example, people who would enjoy old growth should welcome storage programs that lengthen tree rotations. However, water flows from such forests would likely be reduced as older forests tend to evaporate more water. People who like species that depend on younger forests would also be negatively affected by the carbon storage program. The carbon storage program may not be universally accepted as an improvement in forest management by these diverse interests.

In many developing economies, the issue of forest ownership is even more complex. Overlapping interests are typical in many tropical forests. The government or timber concessions may have the right to harvest the timber. But local inhabitants may have the right to harvest the wildlife, collect nontimber forest products or firewood, or graze their animals. What incentives will be given to each group to store more carbon? What if the forest is owned by a village or large family? How will the carbon program interact with the village? It is far more difficult to make transactions with villages or large families than a single forest owner. Current economic analyses have not grasped the cost of this problem at all. In principle, one would need to encourage each party to cooperate with a separate payment.

Equity

There are also important equity issues associated with forest ownership. Some of the poorest people in the world are rural inhabitants of forestlands in tropical countries. Some of the richest people in the world own forest concessions. Global forest programs may pay developing economies to store carbon on forestland, but who actually receives these payments? Do local inhabitants of these forests get any of the compensation? Is the compensation limited to timber concessions? There are important equity issues facing carbon storage programs that have not been resolved. Some of these issues may well raise the cost of the program. They will certainly raise the administrative cost. They may even dramatically affect the social desirability of the programs.

Implications of Measurement and Monitoring Limitations

The measurement and monitoring issues discussed above suggest that a project approach to collecting forest carbon has very serious limitations, particularly in the form of leakage. It may be that only broad national approaches are truly viable. Under a nationalized approached, payments would only be made for total forest carbon at the national level. Internal leakage would be offset, and payments would be made for net changes over time. International leakage would become the responsibility of the country, and the country would need to offset these if it were to receive credits. Internal issues would need to be addressed by the national authority, but failure to do so would mitigate any carbon payments. In addition, this approach would have the advantage of not requiring payment for all forest carbon, but only for positive increments over an agreed base. Broad negotiations (such as those undertaken for Indonesia) that envisage direct payments in return for broad corrective forestry practices and performance might negate the need for precise estimates of forest carbon.

Policy Conclusions

In this chapter, we have explained how carbon storage in forests has enormous potential but also that any meaningful system would be difficult to implement. Forest carbon storage could be responsible for one-quarter of all mitigation and hence cannot be ignored.

There are several important administrative and institutional hurdles that must be overcome for forest carbon storage to be effective. However, many of these hurdles have known solutions. For example, leakage and additionality are serious drawbacks to current forest projects. Universal programs can solve both problems. However, universal subsidies would involve a large income transfer to forest owners. Universal liability would involve a large income transfer away from forest owners. Some combination of liability and subsidies could provide a balanced budget approach that avoids large income transfers and provides the right incentives on the margin. Carbon sequestration and forestry are both dynamic phenomena. The carbon sequestration program must therefore be nimble with respect to time to capture these dynamics accurately. Many policy planners wish to pay only for extra carbon stored. Finally, measurement and verification are important limitations. The program must encourage least-cost measurement technology (such as LIDAR) or the administrative costs could skyrocket.

But even with these administrative innovations, there are two more issues that have yet to be addressed. The carbon storage program must be able to deal with common-property forests (forests that are owned by many). The carbon storage program must also come to terms with equity issues related to local forest inhabitants. One approach may be to nationalize the approach to internalize the leakage problem and place the ownership and equity problems with the national government, which will now have a financial incentive to address these. If carbon storage programs can overcome these administrative hurdles, there is every reason to believe forestry can live up to its mitigation potential. If the programs fail to address these issues, forestry will likely prove to be an ineffective source of carbon mitigation.

References and Suggested Readings

For more information on carbon emissions from land use, see the following:

Houghton, R. A., 2003, "Revised Estimates of the Annual Net Flux of Carbon to the Atmosphere from Changes in Land Use and Land Management 1850–2000," *Tellus Series B Chemical and Physical Meteorology*, Vol. 55B, pp. 378–390.

Intergovernmental Panel on Climate Change, 2007, *Climate Change 2007: Mitigation of Climate Change*. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, 2007 (Cambridge, UK: Cambridge University Press).

Pan, Y., R. A. Birdsey, J. Fang, R. Houghton, P. E. Kauppi, W. A. Kurz, O. L. Phillips, A. Shvidenko, S. L. Lewis, J. G. Canadell, P. Ciais,

R. B. Jackson, S. W. Pacala, A. D. McGuire, S. Piao, A. Rautiainen, S. Sitch, and D. Hayes, 2011, "A Large and Persistent Carbon Sink in the World's Forests," *Science*, Vol. 333, pp. 988–993. DOI: 10.1126/science.1201609.

United Nations FAO, 2010, "Global Forest Resources Assessment 2010." FAO Forestry Paper 163 (Rome: United Nations Food and Agricultural Organization).

For more information on the cost of forest sequestration, see the following:

Richards, K., and C. Stokes, 2004, "A Review of Forest Carbon Sequestration Cost Studies: A Dozen Years of Research," *Climatic Change*, Vol. 63, pp. 1–48.

Sathaye, J., W. Makundi, L. Dale, P. Chan, and K. Andrasko, 2006, "GHG Mitigation Potential, Costs and Benefits in Global Forests," *Energy Journal*, Vol. 27, pp. 127–162.

Sohngen, B., 2010, "Forestry Carbon Sequestration," in *Smart Solutions to Climate Change: Comparing Costs and Benefits*, ed. by B. Lomborg (Cambridge, UK: Cambridge University Press), pp. 114–132.

———, and R. Mendelsohn, 2003, "An Optimal Control Model of Forest Carbon Sequestration," *American Journal of Agricultural Economics*, Vol. 85, No. 2, pp. 448–457.

For more information on designing carbon storage incentives, see the following:

Antle, J. M., S. M. Capalbo, S. Mooney, E. T. Elliot, and K. H. Paustian, 2003, "Spatial Heterogeneity, Contract Design, and the Efficiency of Carbon Sequestration Policies for Agriculture," *Journal of Environmental Economics and Management*, Vol. 46, pp. 231–250.

Marland, G., K. Fruit, and R. Sedjo, 2001, "Accounting for Sequestered Carbon: The Question of Permanence," *Environmental Science and Policy*, Vol. 4, No. 6, pp. 259–268.

Sedjo, R., and G. Marland, 2003, "Inter-Trading Permanent Emissions Credits and Rented Temporary Carbon Emissions Offsets: Some Issues and Alternatives," *Climate Policy*, Vol. 3, No. 4, pp. 435–444.

For more information on the cost of measurement and compliance, see the following:

Antinori, C., and J. Sathaye, 2007, "Assessing Transaction Costs of Project-Based Greenhouse Gas Emissions Trading," Report LBNL-57315 (Berkeley, CA: Lawrence Berkeley National Laboratory).

Macauley, M., and R. A. Sedjo, 2011, "Forests in Climate Policy: Technical, Institutional and Economic Issues in Measurement and Monitoring." *Mitigation and Adaptation Strategies for Global Change*, Vol. 16, No. 5, pp. 489–513.

For more information on programs to store carbon in forests, see the following:

U.S. Department of Agriculture, Farm Services Agency, http://www.fsa.usda.gov/FSA.

Verified Carbon Standard, www.v-c-s.org.

World Bank, 2011, Forest Carbon Partnership Facility, http://www.forestcarbonpartnership.org/fcp/.